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9 – 11 May, 1976
Miami Beach, Florida

Presented by:
Department of Mechanical Engineering,
University of Miami

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United States Nuclear Regulatory Commission
United States Environmental Protection Agency
Duke Power Company
Florida Power and Light Company
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In Cooperation with:
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Editors:
Samuel S. Lee, University of Miami
Subrata Sengupta, University of Miami

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Gratitude is also expressed to all the authors and speakers who made this conference a worthwhile endeavour in scientific communication.

The Session Chairmen and Co-Chairmen deserve special thanks for organizing and conducting the technical sessions.

The support of the numerous students and faculty of the University of Miami is gratefully acknowledged.

The invaluable help of the scientists and administrators of the sponsoring organizations was a key element in making this conference comprehensive. We express our sincerest gratitude to them.

Conference Committee
Miami, May, 1977

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FOREWORD

In the United States, at present, approximately 350,000 MW of steam generating capacity is in the design or construction phase. This is about 80% of all the existing electrical powers generation capacity at the end of 1973. Compounding this trend is the possibility of 5 GW (5000 MW) energy parks which may become reality in the next decade. The possible environmental consequences need serious study. Considering, that for every unit of energy converted to electricity two units are rejected as waste heat, there is a need for utilization efforts.

While the present energy crisis has brought to focus the finite resources of our planet, it is essential to perpetuate the realization that our planet is a finite sink. It is, therefore, imperative to optimize the energy-environment-economy system in an integrated manner.

This conference was organized to provide a forum for inter-disciplinary exchange. The widely scattered biological, economic and engineering state-of-the-art knowledge could then be compiled into a single source, namely, the conference proceedings.

The conference gave equal emphasis to pollution abatement and utilization. Waste heat may come to be regarded as an important energy resource. This document, it is hoped, will serve the stated objectives.

Samuel S. Lee, Chairman
Subrata Sengupta, Co-Chairman

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ABSTRACT

This paper details current Oak Ridge National Laboratory (ORNL) programs, their historical development and possible future directions, concerned with utilization of power plant waste heat. ORNL began exploring beneficial uses of reject heat in the 1960s with studies of controlled environments for agricultural uses. These feasibility studies led to experimental greenhouse efforts and sponsorship of several waste heat utilization conferences. The greenhouse effort resulted in a cooperative program with the Tennessee Valley Authority (TVA) and led to a demonstration of the concept at TVA's Browns Ferry Nuclear Station.

Long-term research is being pursued in the Environmental Sciences Division of ORNL concerning the relationship between temperature, growth rate and food conversion efficiency. Largemouth, smallmouth and striped bass, sauger, crayfish and the clam *Corbicula* are being studied in both constant and oscillating thermal regimes.

An assessment of the relative economic and heat utilization merits of waste heat utilization systems was recently performed, by the Engineering Technology Division, in an effort to indicate those technologies that show the greatest potential for widescale use in the power generating industry. The results indicated that extensive pond aquaculture offered the greatest economic and widescale application potential. This was followed by animal shelters, algal ponds, intensive raceway aquaculture, undersoil heating and greenhouses.

Based on historical program development and the results of the waste heat technology assessment, it appears that future waste heat utilization research at ORNL could include several broad-scale efforts. In the immediate future we will continue to provide technical support for the Browns Ferry demonstration greenhouse. Technical assistance will also be provided for efforts to utilize waste heat from gaseous diffusion plants. Performance data and economic and technical feasibility analyses will be

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performed for integrated power plant-waste heat complex systems and for new utilization technologies.

Long range goals indicate the need for studies concerning mass balance and zooplankton production estimates of sewage oxidation ponds. Development of a comprehensive program exploring thermally enriched pond polyculture appears to be desirable. This program could investigate economic and technical considerations of producing low-cost protein using power plant reject heat.

INTRODUCTION

This paper traces programs at the Oak Ridge National Laboratory (ORNL) dealing with power plant reject heat research from their inception to the present. Results of recent studies are outlined to indicate the scope of present efforts. Possible future directions for research in the area at ORNL are also presented.

Research dealing with power plant reject heat has been performed primarily by two divisions within ORNL. The Engineering Technology Division (ETD) program, begun in the late 1960s, has concentrated on beneficial uses of reject heat. The Environmental Sciences Division (ESD) program, begun in the early 1970s, has been primarily directed at exploring the effects of thermal discharges on natural ecosystems. Both of these programs have been supported by the Energy Research and Development Administration (ERDA).

HISTORICAL DEVELOPMENT OF PROGRAMS

The Environmental Sciences Division has carried out research on growth and food conversion of aquatic species for several years. The work began as studies on thermal pollution, an examination of the effects of elevated temperature resulting from the cooling cycle in electric generating plants. The species studied have included the largemouth bass, *Micropterus salmoides*, the striped bass, *Morone saxatilis*, the sauger, *Stizostedion canadense*, the freshwater clam, *Corbicula manilensis* and the crayfish, *Cambarus bartoni*.

The ETD beneficial uses of waste heat program began in 1969 as a result of a growing concern over thermal pollution [1]. These efforts began with analytical studies of greenhouse and animal rearing applications for waste heat [2-7]. The studies were primarily directed at investigating engineering details and technical feasibility of the systems.

The system examined for heating and cooling greenhouses and animal shelters is illustrated in Fig. 1. It involves the use of a conventional pad and fan system with finned-tube coils mounted downstream of the pads.

The pads are typically filled with a fibrous material. Condenser cooling water drips vertically down along the fibers while air flows horizontally through the pad. The air is heated or cooled depending on the ratio of sensible to latent heat transfer. The cooled water is collected at the bottom of the pad and returned to the condenser.

Warm water from the condenser can also be pumped through the finned-tube coils. The air, coming from the pads, is heated and dried by the addition of sensible heat from the fins. By varying the relative fractions of water pumped through the pads and coils and the airflow rate, the temperature and humidity of the air entering the greenhouse or animal shelter can be adjusted. This system can be used for summer cooling and winter heating. Heated or cooled air can be allowed to pass through the house and out the other end through exhaust fans. Under certain environmental conditions, such as extremely cold weather, automatically controlled louvers would permit recirculation of the air through the attic.

Further analytical studies [8] considered aquacultural uses of waste heat. This study concentrated on shrimp production using waste heat to enhance growth. The primary emphasis of the program, however, continued to be greenhouse applications.

These feasibility studies led to experimental greenhouse efforts [3] and sponsorship of waste heat workshops in Oak Ridge in 1970 and Gatlinburg, Tennessee in 1971 [9]. The greenhouse experimental efforts were conducted in a small 6.1 × 14.6 m (20 × 48 ft) Mylar greenhouse constructed at ORNL. The aspen fiber pads were fed with 40°C (105°F) water at a rate of 37.2 ℓ/m (3 gpm/ft) of pad length from an air conditioning cooling tower. The greenhouse was operated from the fall of 1970 to the summer of 1971 to determine the operating characteristics of the pad and finned-tube coil system in the heating and cooling mode.

The ORNL experimental greenhouse efforts led to a joint greenhouse program with the Tennessee Valley Authority (TVA). This program has led to the construction and operation of a pilot greenhouse for waste heat research which is located at the TVA facilities in Muscle Shoals, Alabama. The greenhouse, shown schematically in Fig. 1, is a conventional aluminum-framed glass-glazed structure. An electric boiler is used to simulate the discharge from a power plant condenser.

Aspen pads were initially used as the evaporative pad material. However, experimental work performed at ORNL [10] demonstrated that CELdek, a cooling tower packing manufactured by Munters Corporation of Fort Meyers, Florida, was a superior heat and mass transfer media. The aspen pads were replaced by CELdek in 1975 prior to planting the fall crop.

Results from this experimental effort have been encouraging [11, 12] and TVA has decided to construct a demonstration half-acre greenhouse at their Browns Ferry (Alabama) Nuclear Station. Condenser water from the nuclear station will be used as the warm water source for the pad and finned tube system.

CURRENT PROGRAMS

Part of the current research, performed in the ESD of ORNL, deals with growth and food conversion of aquatic species. The species studied include the largemouth bass, *Micropterus salmoides,* the striped bass, *Morone saxatilis,* the sauger, *Stizostedion canadense*, the freshwater clam, *Corbicula manilensis* and the crayfish, *Cambarus bartoni*.

Growth rates of yearling largemouth bass [40 to 200 g (0.09–0.4 lb)] were fastest in the 26 to 28°C (79–82°F) range [13]. Growth rate decreased progressively at temperatures above 28°C until growth ceased near 35.5°C (96°F). The estimated 35.5°C for zero growth is 0.9°C (1.6°F) less than the ultimate incipient lethal temperature for largemouth bass [36.4°C (94°F)] reported by Hart [14]. No temperatures below 24°C (1.6°F) were tested.

The growth-temperature response curve for striped bass, *Morone saxatilis*, suggests an optimum growth range of 23 to 26°C (73–79°F). The estimated temperature of zero growth is 33.5°C (92°F). Food conversion efficiency and feeding rate respond to temperature in a manner similar to growth; they both accelerate from 12°C (54°F) to optima of 23 and 25°C (73 and 77°F) for conversion and consumption, respectively, and then decline steeply as temperature increases. These data were generated with subadult striped bass fed an excess ration. Adult fish are likely to have lower preferred and optimum growth temperatures. Some preliminary work suggests a decrease in optimum and zero growth temperatures as ration is reduced.

Studies of the sauger, *Stizostedion canadense,* are in progress at the present time. To date, digestion rate has been examined at temperatures between 5 and 15°C (41 and 59°F). In these experiments, it has been found that digestive rate is very similar at 5 and 10°C (41 and 50°F), and takes a sudden jump between 10 and 15°C (50 and 59°F). Future efforts will be directed at examination of the same process at higher temperatures, as well as defining the (thermal) region of maximum growth rate.

Growth rates and survivorship of young-of-the year crayfish, *Cambarus bartoni,* were measured from 5 to 30°C (41–86°F) at 5°C (9°F) intervals. Growth rate was maximum at 25°C (77°F), but survivorship was greatest at 20°C (68°F). The best temperatures for culturing this species of crayfish probably lie between 20 and 25°C. The maximum temperature this crayfish can tolerate for more than one week is about 33°C (91°F). Growth and survivorship were minimal at 5°C. An apparent problem in culturing crayfish is their propensity for eating their cohorts, particularly molting individuals.

Studies of the freshwater clam, *Corbicula manilensis,* are in their initial stages. In field studies associated with heated power plant discharges, maximum growth appears to be at around 24°C (75°F). Also, a diurnally oscillating thermal regime has been correlated with higher growth rate. These data are preliminary, however, and should be regarded as such.

All these studies have provided an in-house expertise on thermal effects which is directly applicable to problems of waste heat aquaculture.

The current ETD waste heat utilization program is primarily concerned with support for the Browns Ferry demonstration greenhouse and technical and economic assessments of waste heat utilization technologies. Support of the Browns Ferry project has thus far led ORNL to assume responsibility for the greenhouse design. This design has recently been completed by the Environmental Research Laboratory of the University of Arizona, under contract to ORNL. The first planting is expected to take place in the fall of 1977. Present and future support of this effort will include technical support and experimental verification, at ORNL, of any unique features of the greenhouse design.

The technical and economic assessment facet of the program has led to investigation of economic aspects of waste heat use in greenhouses, new aquaculture systems to utilize waste heat, overall assessments of waste heat utilization technologies and utilization of waste heat from gaseous diffusion plants. The effort to utilize gaseous diffusion plant waste heat has primarily involved technical support for various groups interested in the concept. Information concerning the amount of heat and temperature levels available for on- and off-site use has been obtained for the three ERDA Gaseous Diffusion Plants at Portsmouth, Ohio; Paducah, Kentucky and Oak Ridge, Tennessee. Details of the cooling water piping system have also been obtained and possible tapping points (to take the cooling water to a heat exchanger for off-site use of the heat) have been identified. This information was obtained at ERDA's request and forwarded to the ERDA committee examining this question. An analysis of the overall technical and economic aspects of using gaseous diffusion plant waste heat is presently being prepared by ORNL.

Technical assistance is also being given to the Oak Ridge Chamber of Commerce in conjunction with their efforts to establish an industrial park near the Oak Ridge Gaseous Diffusion Plant (ORGDP). This industrial site would utilize some of the ORGDP waste heat for the industries in the complex. Heat would be supplied to the site from the ORGDP cooling water using a heat exchanger to isolate the ORGDP water from the industrial heat supply. The heat would then be piped about a mile to the industrial park. Preliminary ORNL estimates, using a ten year amortization period and a 10% cost of money, indicate the cost of delivered energy would be about \$0.64/GJ (67¢/10^6 Btu). If the energy usage varied on a seasonal or daily basis, the heat cost would rise.

An analysis [15] was performed by ORNL to determine the economic feasibility of heating greenhouses with power plant reject heat. The recently updated [16] results indicate that for a 2.5 ha (10 acre) greenhouse located within 305 m (1000 ft) of the power station, waste heat is the economic choice, when compared to fossil fuels at \$1.66–\$2.37/GJ (\$1.75–\$2.50/10^6 Btu), for greenhouse winter heating if the condenser cooling water outlet temperature is 27°C (80°F) or above. If the condenser outlet temperature drops to 21°C (70°F), the economic feasibility of using waste heat depends upon climate and the cost of fossil fuels. For condenser outlet temperatures below 21°C (70°F) the waste heat system is not economically feasible.

These results are based on a greenhouse design similar to that illustrated in Fig. 1. For the purposes of this study the finned tube exchanger was not included in the heating system design.

Examination of typical U.S. greenhouse fixed and operating costs and revenues, for production of two tomato crops per year, indicated that the use of fossil fuels resulted in an operating loss for all but mild climates. As illustrated in Fig. 2, use of waste heat with 27°C (80°F) water results in an operating profit for all U.S. climatic conditions. Use of waste heat at higher temperatures produces similar profits, whereas, use of waste heat at 21°C (70°F) can be profitable for only some climatic conditions. These results are based on capital recovery at 8% over 20 years and power costs of 2¢/kWhr.

These studies concluded that the feasibility of using waste heat for greenhouse heating depended upon the available condenser cooling water outlet temperature. Therefore, any decision concerning the feasibility of waste heat use for greenhouses should include consideration of the power plant design.

As previously mentioned the ESD program has provided the necessary biological expertise for waste heat aquaculture studies. Drawing on this expertise a study [17] was recently performed by ETD to assess the potential use of waste heat for low-cost protein production via aquaculture. After surveying current aquaculture efforts in the United States, it became evident that the major portion of this work concentrates on intensive culture of species such as lobster, shrimp, trout, salmon and catfish. The high cost of these species, arising partly from the need for expensive, high protein feed (typically 30 to 40% of operating costs are due to feed costs), limits their market and, therefore, the potential for waste heat utilization.

This study evaluated an aquaculture system using extensive culture techniques and natural ecosystem food supplies. Fin and shellfish that feed on the lower trophic levels of the food chain were utilized in the system. Addition of waste heat was used to provide regulated growth temperatures for phytoplankton and zooplankton cultures and for the fish systems. Planktonic growth is further enhanced by the addition of nutrients available from a variety of waste streams.

The planktonic biomass is used as the food source for fish culture and polyculture techniques are employed to utilize all feeding niches in the pond.

Alternative biological systems proposed for the waste heat aquaculture facility producing low-cost protein have been based on the following assumptions: (a) a minimum temperature of 20°C (68°F) can be maintained through the year, (b) a controlled input of nutrients (carbon, nitrogen and phorphorous) is available, (c) mud bottomed ponds, 1 to 2 m (3 to 6 ft) deep, are used. Assumption (a) essentially envisions utilization of waste heat from a power plant using a closed loop cooling system. For this preliminary study, the species selection concentrated on fresh-water varieties because the majority of power plants, especially nuclear plants, are located inland. It should be noted, however, that suitable species (such as striped mullet, croaker, tarpon and sheepshead) are available for coastal sites.

The general design features of the system, as conceptualized by ESD personnel, are illustrated in Fig. 3. Conceptually, the system functions in the following manner. A nutrient stream is heated using power plant waste heat and flows into Pond I with an appropriate amount of diluent. Algae begin the uptake of nutrients, in Pond I, and are grazed upon by zooplankton. The overflow from Pond I, laden with algae and zooplankton, flows into Pond II where fish are grown. In Pond II fish consume algae, zooplankton, aquatic macrophytes (grown in the pond mud bottom) and benthic organisms. Water flows into Pond III laden with fish waste products and algae are again used to remove the nutrients. In Pond IV clams are used as living biofilters, straining algae and bacteria out of the water. Crayfish are used in Pond IV to consume the clam wastes. Protein production is, therefore, concentrated in fish, clams, and crayfish. A final "cleaning" pond containing aquatic vegetation will probably be necessary to produce a clean effluent.

A number of alternative biological associations is available for Pond II. As stated, the study concentrated on fresh-water species since most power plants are inland. Detailed analysis was performed for a carp and tilapia association. Table I lists the species involved in each association along with their feeding niche and the name by which they are commonly known.

Economic analysis of the system indicated that the system is feasible. The projected rate of return is shown in Fig. 4 as a function of the interest rate and lifetime for amortization of the capital investment. Assuming that capital items are recovered at 8 3/4% over 20 years, the annual pretax rate of return is 63%. These economic estimates were based on product prices that reflected the goal of low-cost protein. The fish were assumed sold for \$0.66/kg (\$0.30/lb) and the clams \$1.34/kg of clam meat (\$4.38/bu), which is about one-fourth the current market price for clams. The crayfish commanded a high price [\$2.75/kg (\$1.25/lb)] but did not represent a significant fraction of the system income.

In an effort to determine which heat utilization technologies offered the greatest potential for wide-scale use in the power generating industry, an assessment [18] of the relative economic and heat utilization merits of these systems was made. The systems analyzed in this report included: (1) glass glazed greenhouses producing one crop per year, (2) undersoil heating, (3) algal ponds, (4) extensive pond aquaculture, (5) intensive raceway aquaculture and (6) animal shelters. Intensive aquaculture was used to indicate systems that use concrete raceways, high protein feeds and oxygenation systems in an effort to achieve the maximum yield from a body of water. Extensive systems are those that utilize natural ecosystem food chains and maximize growth by controlling water temperature.

The algal and aquaculture systems included both open and closed system operation. Open systems are those that use the condenser cooling water directly in the heat utilization system. Closed systems employ a heat exchanger to separate the two streams.

The systems were designed to accommodate the yearly cooling needs of a 1000 MW(e) power plant. Based on the complex sizes indicated in Table II, unit annual costs were estimated for these systems. The heat utilization system costs presented in Fig. 5 include only those costs directly associated with the heat utilization system. This includes capital items (greenhouses, raceways, etc.), land acquisition [if the system land requirements exceed the normal utility land area purchase of about 125 ha (500 acres)], and power costs associated with operation of the complex as a heat dissipation system.

Costs for circulating the condenser effluent through the heat utilization complex and returning it to the condenser are shown as the warm water distribution costs in Fig. 5. The heated water distribution costs were estimated assuming a square layout for the complex and use of prefabricated steel pipe conduit.

Several systems are not capable of using the waste heat in summer and cooling towers must be constructed to accommodate this load. These costs are illustrated in Fig. 5 as additional cooling system costs.

Based on these unit annual costs, products were selected for the heat utilization systems. These product selections and their probable markets are given in Table III.

Given the product selections, the projected unit annual revenue was computed for each system. These results are presented in Fig. 6.

Using the unit annual revenue and cost estimates from Figs. 5 and 6, an economic index was computed to compare the economic potential of the systems. The economic index used was the ratio of the unit annual revenue and the unit annual cooling cost (the sum of the heat utilization system cost and, if required, the additional cooling system cost). This index was used to determine which systems would be economically attractive if constructed for use as a power plant cooling system.

The economic index results are presented in Fig. 7. It should be noted that site specific conditions, alternate economic assumptions or alternate system designs could alter the economic results. In areas that permit double cropping of tomatoes, for instance, the revenue figures for greenhouse tomato production would double. Use of plastic rather than glass greenhouses would reduce the capital costs by about 40%, but would result in higher operating costs because the house would need recovering every year or two. Likewise, plastic lined earthen raceways could be used in place of concrete raceways for intensive aquaculture. This would result in a 50% reduction in capital costs but would increase operating costs associated with cleaning the settling basin required in such systems.

A heat utilization index was similarly used to determine if product market constraints would restrict wide-scale use of the system. Based on the product selections from Table III, the area required to satisfy 100% of the U.S. demand for the system products was computed. The implementation merit index, presented in Fig. 8, was computed by dividing the area required to satisfy 100% of the U.S. demand by the area required to satisfy the heat dissipation needs of a 1000 MW(e) power plant. This index, therefore, indicates the number of 1000 MW(e) power plants required to satisfy the total U.S. demand for products from the heat utilization system. Essentially it is an indicator of the potential impact the system could have in the power generating industry.

Based on the economic and implementation indices, from Figs. 7 and 8, the technologies were ranked to indicate which showed the greatest potential for wide-scale use in the power generating industry. A summary of these rankings is presented in Table IV. The three top ranked technologies (extensive pond aquaculture, animal shelters and algal ponds) all showed an economic index greater than one and a high implementation index. The other technologies usually ranked poorly in at least one of the indices.

The results of this assessment indicate that efforts to demonstrate the three top ranked technologies should be pursued. Efforts concerning the other technologies should address the specific areas (economic or implementation) that caused a lower ranking.

POSSIBLE FUTURE PROGRAM DIRECTIONS

Based on historical program development at ORNL, it seems likely that the ESD and ETD programs will continue in some of the areas in which they are currently involved. The ETD program on beneficial uses, for example, will continue with technical and economic assessments of waste heat utilization systems. Future studies will likely include performance estimates for integrated power plant-waste heat complex systems. New waste heat utilization systems will be analyzed and evaluated. Technical support will continue to be given to the Browns Ferry demonstration project.

One of the proposals for future work in the ESD is a study of sewage oxidation ponds. It has been noted that the domestic sewage oxidation ponds at ORNL support luxuriant and quite stable growths of algae and zooplankton. As such they have potential as a nutrient base for an aquaculture system. The zooplankton occurring naturally in the ponds is essentially a monoculture of an extremely large morph of *Daphnia pulex*, an ideal zooplankivorous fish food. It is proposed that mass balance studies be run on the ponds to assess the fish crop and production rate supportable on a resource of this type.

The main thrust of proposed work at ESD in waste heat utilization is at the present time toward integrated-system polyculture. The results of the assessment study and the successful collaboration of ETD and ESD personnel in the aquaculture study indicate the possibility for a broad scale, multidisciplinary effort to expand the aquaculture effort begun by ESD. The development of a comprehensive program exploring thermally enriched pond polyculture appears to be desirable using this multidisciplinary approach. Using this approach ETD would be responsible for engineering and technical and economic assessment aspects of the project while ESD would deal with the biological aspects of the system.

As a first step, research has been funded under the Exploratory Studies program at ORNL at a level that will permit preliminary examination of the concept and an assessment of its biological and economic feasibility. It is anticipated that this study will provide the necessary data base on which to build an expanded aquaculture program.

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TABLE I. SPECIES ASSOCIATIONS FOR THE PROPOSED WASTE HEAT AQUACULTURE SYSTEM

Alternative	Species	Primary feeding niche
1. Carp association		
Grass carp	*Ctenopharyngodon idellus*	Large floating plants
Bighead carp	*Aristichtys nobilis*	Midwater zooplankton
Silver carp	*Hypophthalmichtys molitriy*	Phytoplankton in midwaters
Mud carp	*Cirrhinus molitorella*	Bottom feeder, feces
Common carp	*Cyprinus carpio*	Bottom feeder
Black carp	*Mylopharyngdon piceus*	Mollusks
2. Tilapia association		
Nile tilapia	*Tilapia nilotica*	Omnivorous (esp. plants)
Java tilapia	*Tilapia mossambica*	Omnivorous (plankton)
Blue tilapia	*Tilapia aurea*	Plankton
Congo tilapia	*Tilapia rendalli* (*T. melanopleura*)	Rooted aquatic vegetation

TABLE II. DESIGN SUMMARY FOR WASTE HEAT UTILIZATION COMPLEXES

System	Minimum heat rejection (MW/acre)	System size required for 1000 MW(e) station		Additional cooling required (MW)
		Heat rejection system (acre)	Total complex[a] (acre)	
Greenhouse	2.00	1,000	1,100	2000[b]
Algal pond — open system	2.80	714	785	0
Algal pond — closed system	2.80	714	785	0
Extensive pond aquaculture — open system	2.70	740	814	0
Extensive pond aquaculture — closed system	2.70	740	814	0
Undersoil heating	0.16	12,500	12,500	0
Intensive raceway aquaculture — open system	2.00	1,000	1,100	0
Intensive raceway aquaculture — closed system	2.00	1,000	1,100	0
Animal enclosures				
Broilers	2.50	800	880	2000[b]
Swine	2.50	800	880	2000[b]

[a] Includes 10% for access roads and other auxiliaries.

[b] Warm water not used in the summer.

TABLE III. PRODUCT SELECTION INFORMATION

System	Products	Market
Greenhouse	Tomato	Fresh
	Cucumber	Fresh
	Lettuce	Fresh
Undersoil heating	Tomato	Fresh
	Strawberries	Fresh or processed
	Bush beans	Fresh
Pond aquaculture	Tilapia	Block fish
	Carp	Block fish
	Clams	Fresh or processed
	Oysters	Fresh or processed
Algal ponds	Algae	Fish meal or processed for fuel
Raceway aquaculture	Catfish	Fresh
	Trout	Fresh
	Salmon	Fresh
	Shrimp	Fresh and frozen
Animal enclosures	Broilers	Fresh
	Pork	Fresh or processed

TABLE IV. RANKING OF WASTE HEAT UTILIZATION TECHNOLOGIES

Ranking	System
1	Extensive pond aquaculture
2	Animal shelters
3	Algal ponds
4	Intensive raceway aquaculture
5	Undersoil heating
6	Greenhouses

MO

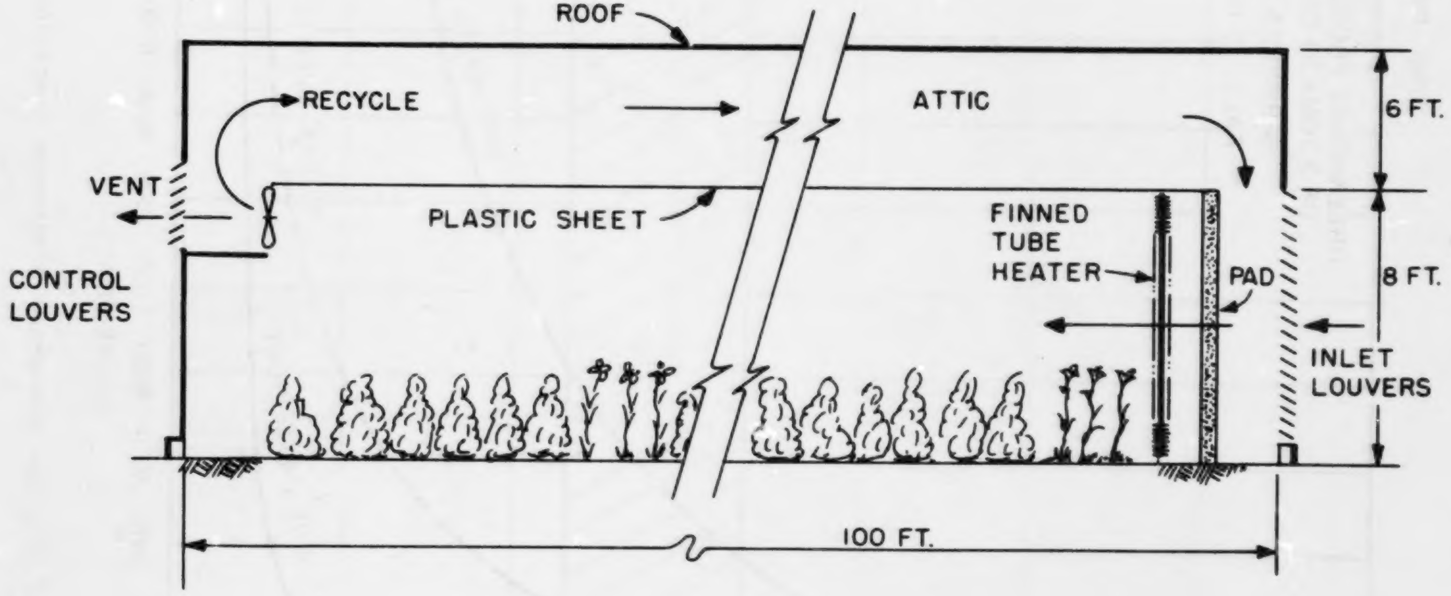
ROOF
RECYCLE
ATTIC
6 FT.
VENT
PLASTIC SHEET
CONTROL LOUVERS
FINNED TUBE HEATER
PAD
8 FT.
INLET LOUVERS
100 FT.

Fig. 1. Schematic of Greenhouse or Animal Shelter Heating System.

ORNL-DWG 77-6281

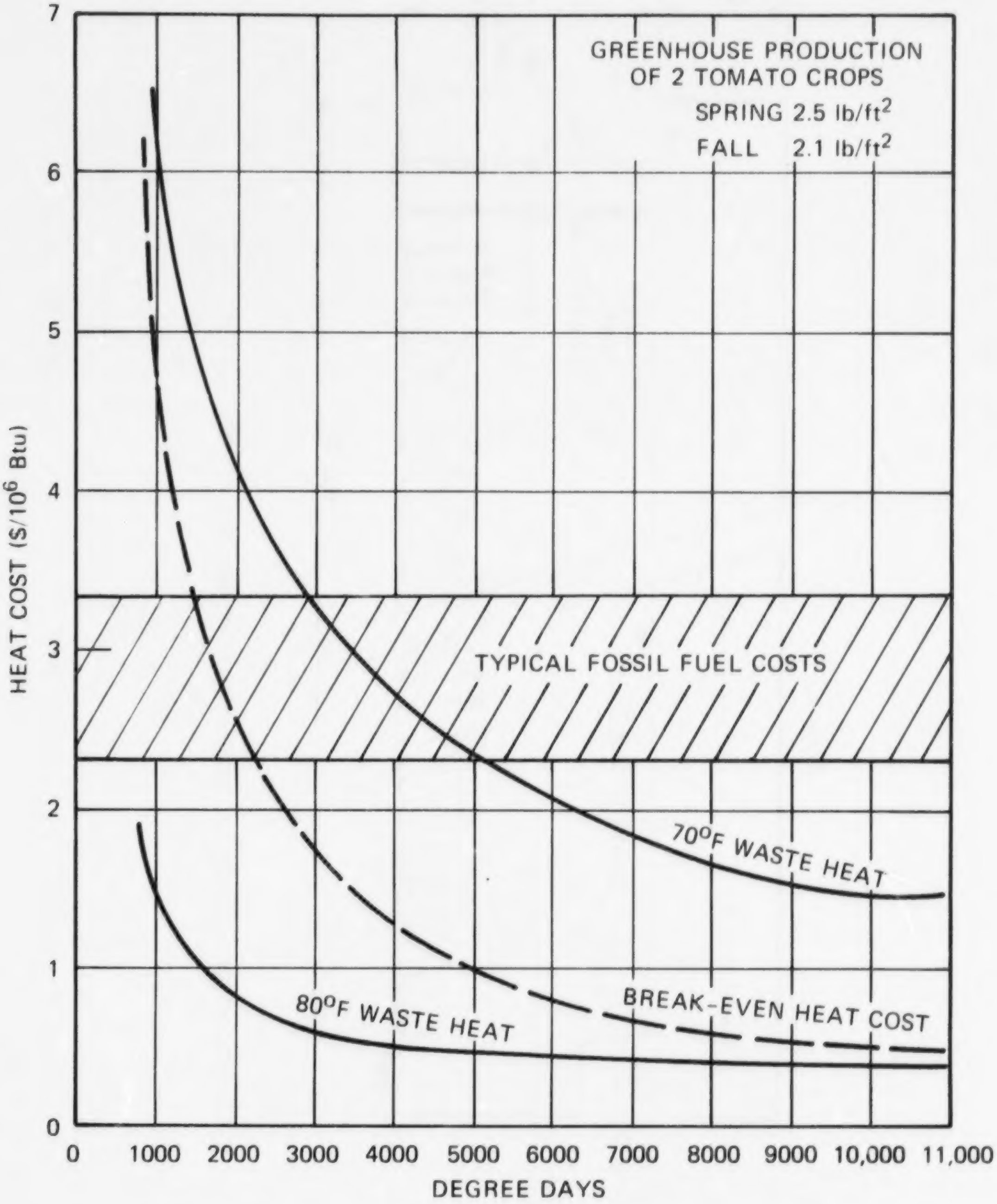

Fig. 2. Maximum Heat Cost for Greenhouse Break-even Operation.

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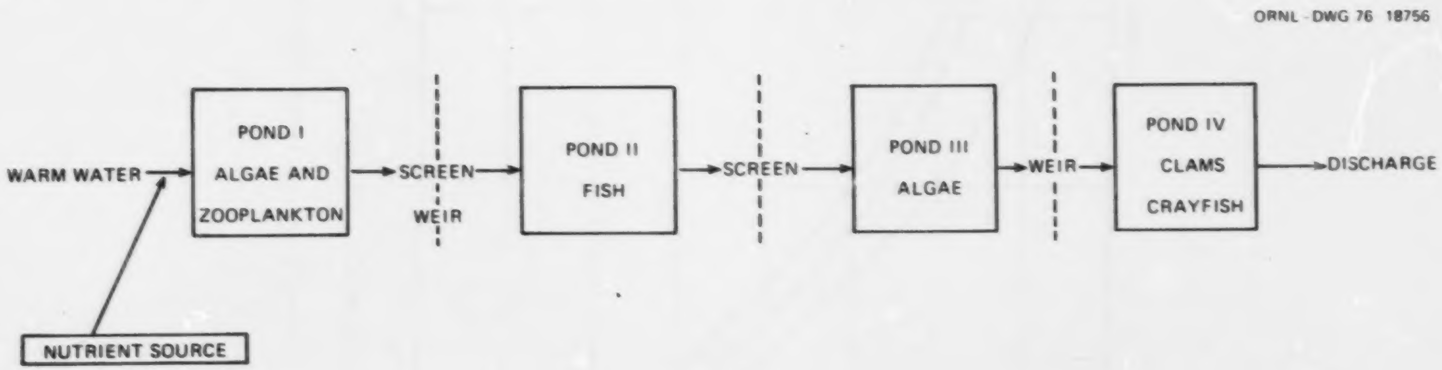
ORNL-DWG 76 18756
WARM WATER
NUTRIENT SOURCE
POND I
ALGAE AND
ZOOPLANKTON
SCREEN
WEIR
POND II
FISH
SCREEN
POND III
ALGAE
WEIR
POND IV
CLAMS
CRAYFISH
DISCHARGE

Fig. 3. Schematic Diagram of Proposed Waste Heat Aquaculture System.

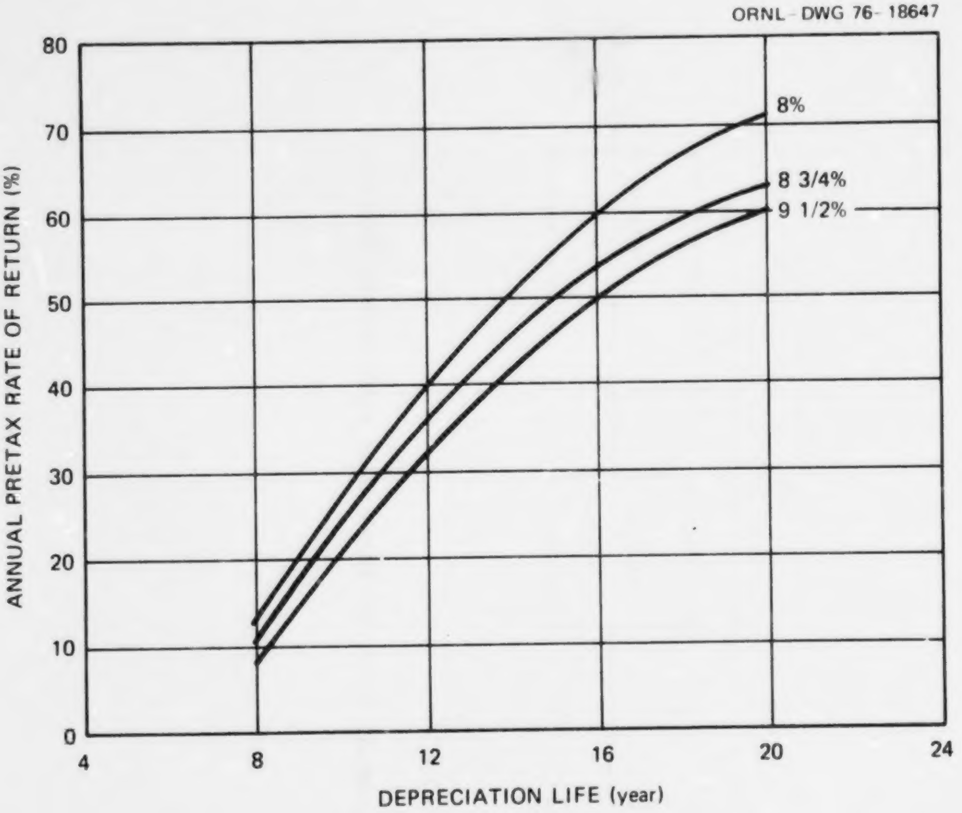

Fig. 4. Rate of Return for Proposed Aquaculture System.

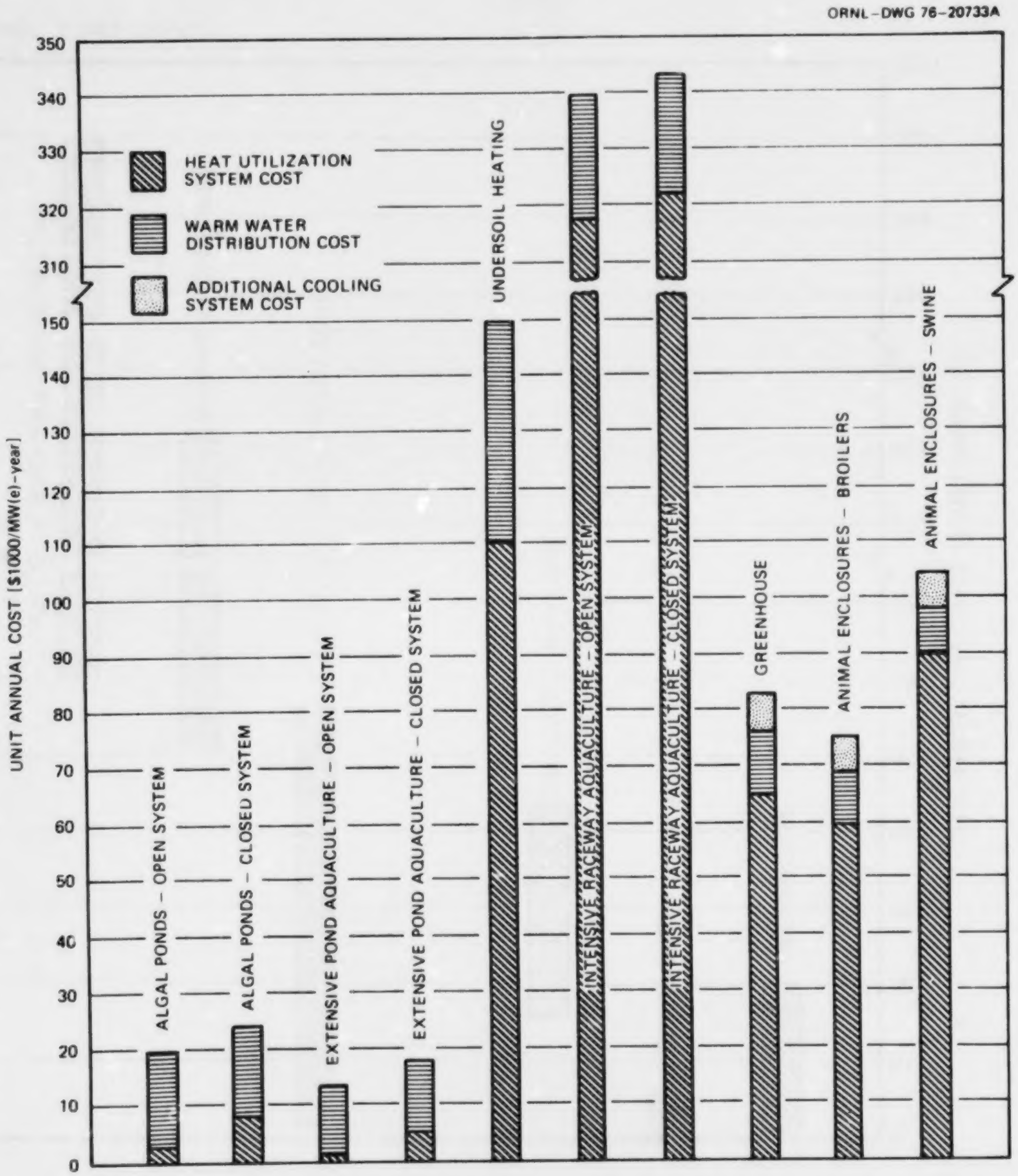

Fig. 5. Cost for Utilizing all Reject Heat from a 1000 MW(e) Power Plant.

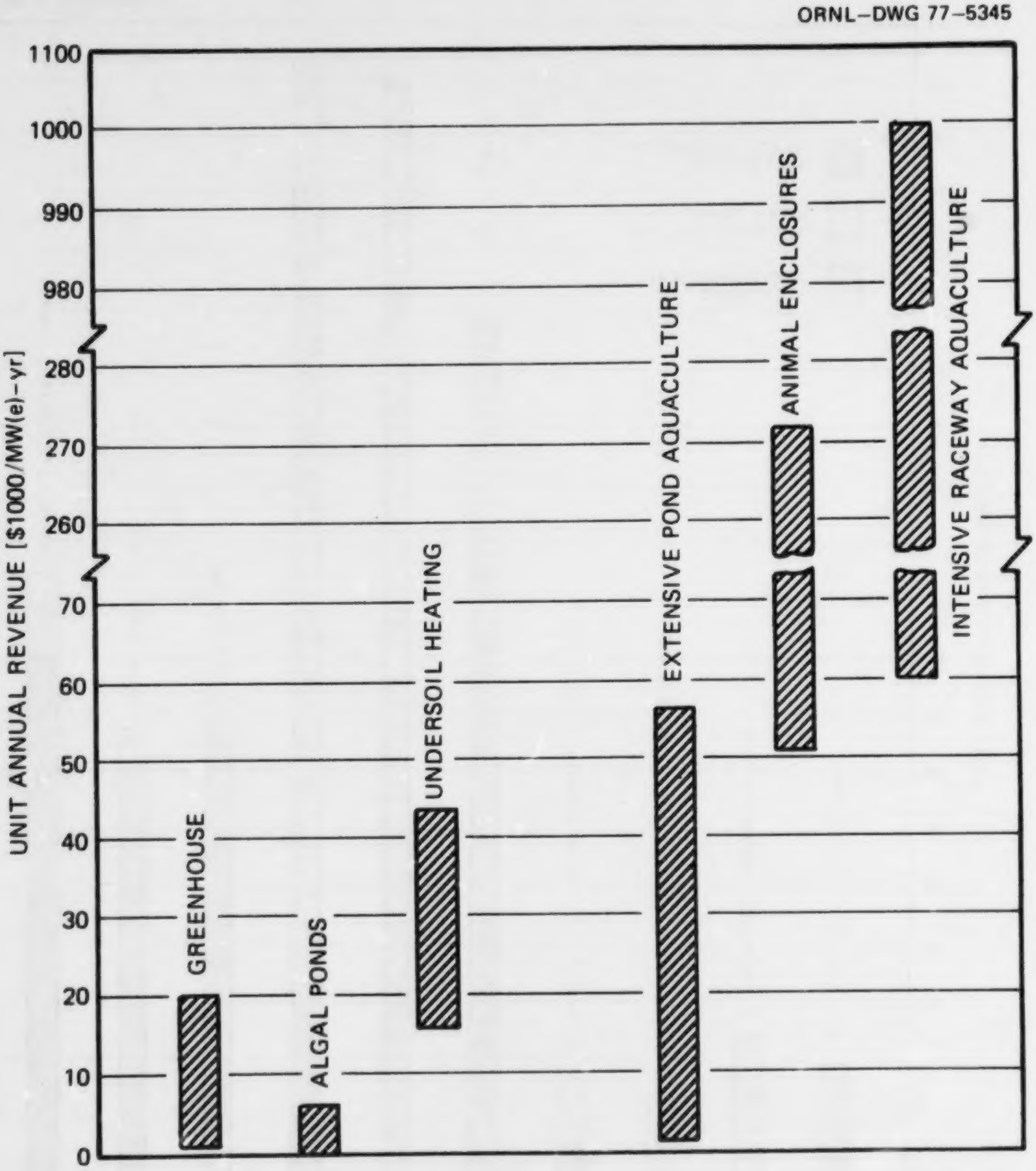

Fig. 6. Unit Annual Revenue.

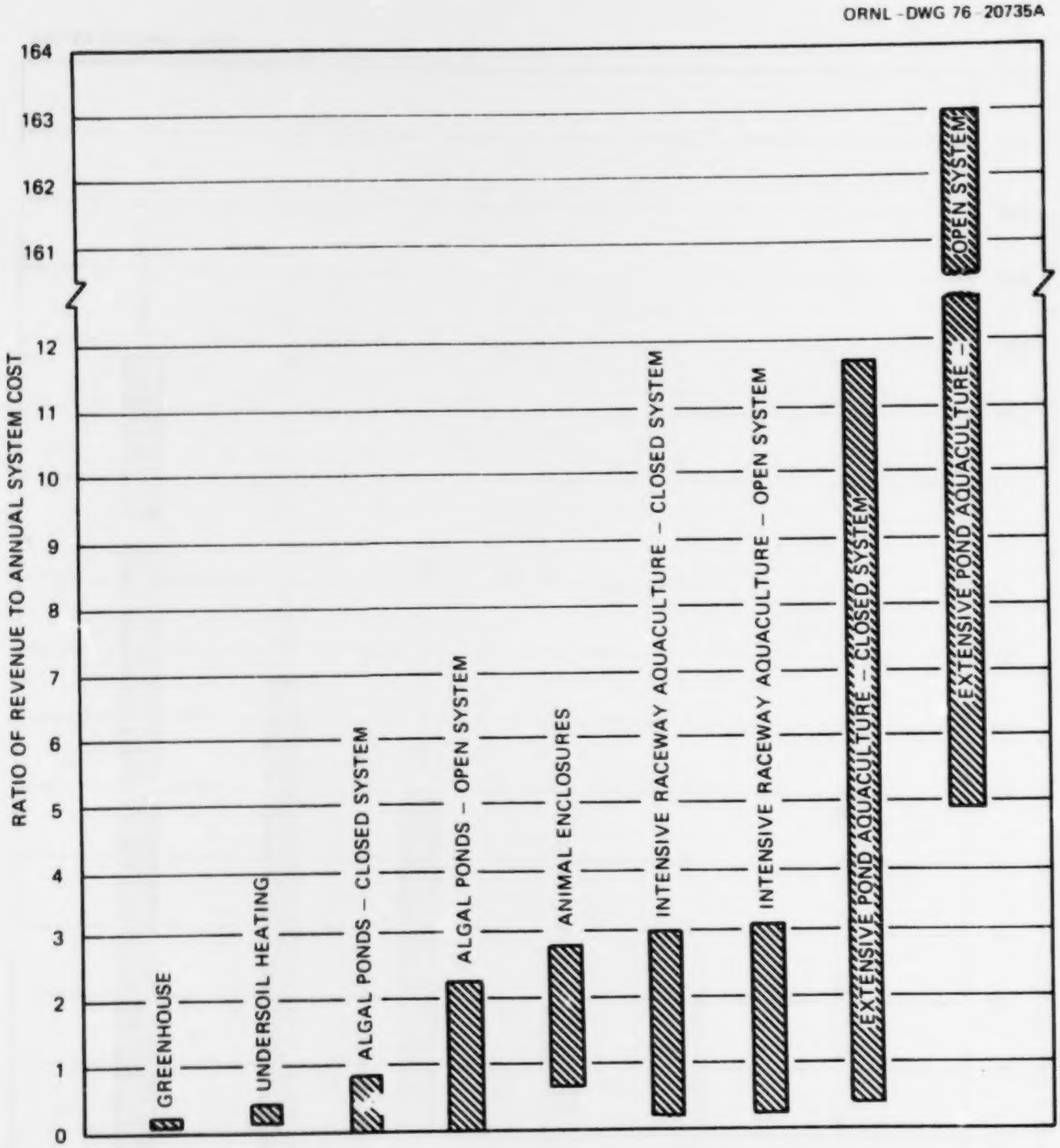

Fig. 7. Economic Index for Waste Heat Utilization Systems.

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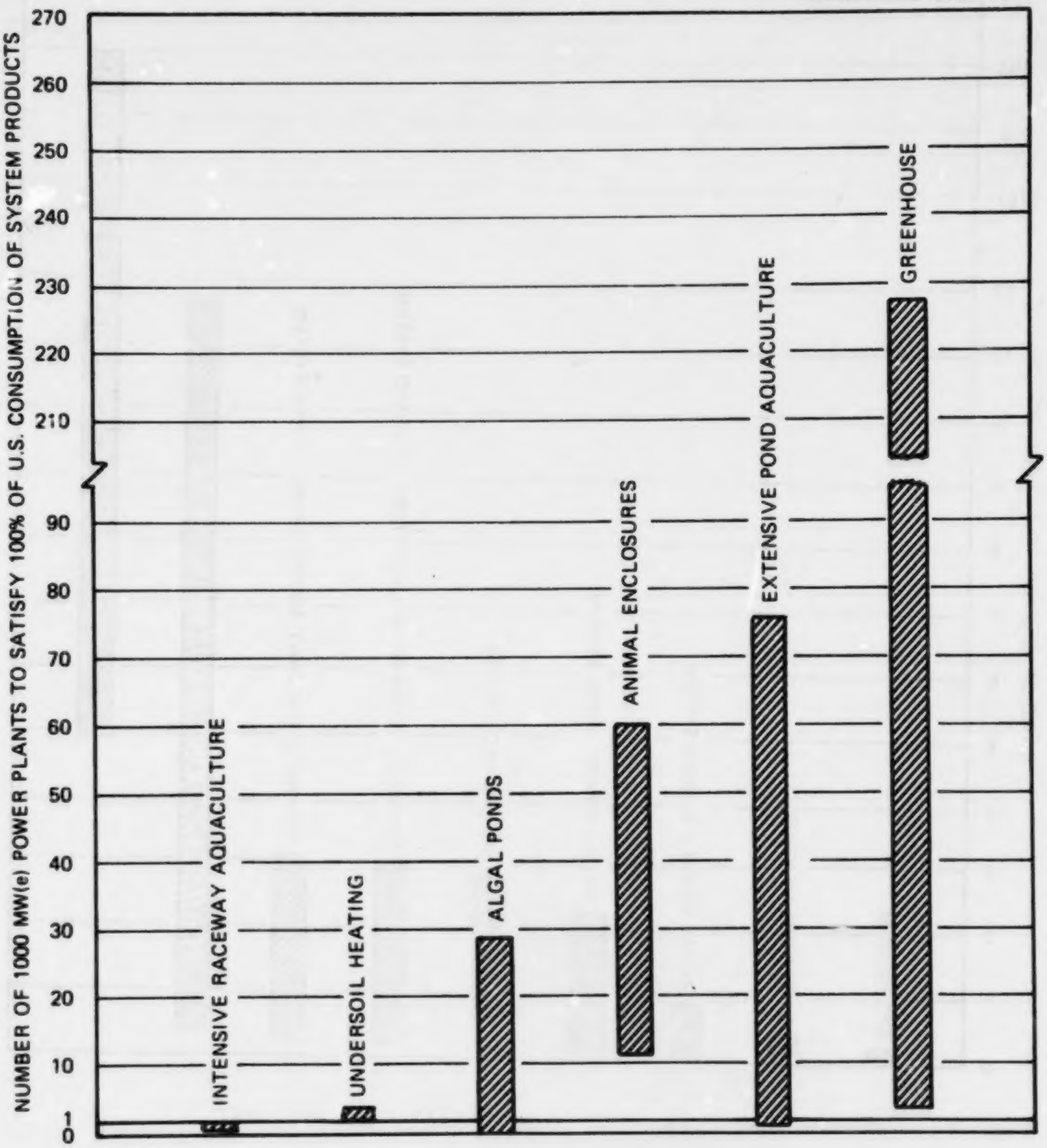

Fig. 8. Implementation Index for Waste Heat Utilization Systems.

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DRIFT FROM THE CHALK POINT NATURAL DRAFT BRACKISH WATER COOLING TOWER: SOURCE DEFINITION, DOWNWIND MEASUREMENTS, TRANSPORT MODELING

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ABSTRACT

Drift data are presented which were acquired in and around PEPCO's Chalk Point Unit #3 natural draft cooling tower. Source data in the form of droplet size spectra and salt mass emission were acquired via an equal area traverse near the exit plane of the 400 foot tower and in the 712 foot stack. Results show that the drift fraction of the tower is within the manufacturer's guarantee when the tower circulating water flow rate is assumed to be the design value (260,000 gpm). Droplet spectra show an average droplet mass median diameter of 79 μm for the measurement series. Results show further that the stack which employs a brackish water scrubber may present an interference to cooling tower drift modeling studies.

Downwind measurements at ground level of airborne salt concentration and droplet number per unit volume of air were compared with predicted results from drift transport models using the source data as input. Comparison of predicted and measured downwind values show reasonable agreement.

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INTRODUCTION

This paper presents selected results from a major phase of the Chalk Point Cooling Tower Project (CPCTP), a research and monitoring endeavor administered by the State of Maryland Power Plant Siting Program (PPSP) and supported by the State of Maryland, the Electric Power Research Institute (EPRI), the U. S. Energy Research and Development Administration (ERDA) and the Potomac Electric Power Company (PEPCO). The original objective of the CPCTP was to assess the effects of cooling tower salt water drift on vegetation in the area surrounding the Chalk Point site. The tower under investigation provides cooling for Unit #3 of the Potomac Electric Power Company's Chalk Point Generating Station located on the Patuxent River, approximately 40 miles southeast of Washington D.C. This large hyperbolic natural draft crossflow tower was built by the Marley Company and utilizes brackish Patuxent River water for make-up, hence the salt drift which Marley paid special attention to in the drift eliminator design. The tower stands 400 feet high and its design circulating water flow rate is 260,000 gpm.

Concern over the effects of salt drift on the Maryland tobacco grown in the Chalk Point vicinity was a prime motivating factor in the Chalk Point drift program beginning. Although ascertaining the environmental impact of the salt drift remains a major objective, the program has expanded in scope to include data acquisition in a number of related areas relevant to the siting of large power plants with natural draft cooling towers. One of the primary objectives of the present program is to "select, improve and validate salt drift transport and deposition models (or a model) suitable for use in predicting salt drift distribution from natural draft cooling towers"[1]. Other objectives include development of an archival data base suitable for use by other investigators and determination of the range of variation of cooling tower emission parameters over a year's meteorological and plant load conditions.

Environmental Systems Corporation (ESC) of Knoxville, Tennessee is assisting the State of Maryland in meeting the CPCTP objectives together with the University of Maryland, the Applied Physics Laboratory of the Johns Hopkins University, and Meteorology Research Incorporated. Before Unit #3 came on-line in May, 1975, ESC was charged with the responsibility of acquiring background ambient salt concentration data in the Chalk Point environs. Since that time, ESC has conducted measurements in and around the cooling tower for ultimate use in salt drift and vapor plume environmental impact evaluation and model verification and refinement. A broad view of the Chalk Point project has been presented in earlier papers[2]. The objective of this paper is to present selected results of CPCTP source and downwind drift measurements together with results of model calculations which link these two groups of data. These data represent only a small fraction of the drift data which have been acquired since the Unit #3 cooling tower came

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on-line and the ESC drift measurement program represents only part of the total data acquisition effort. Other areas of data acquisition within the Project include visible plume photography, meteorological measurements, airborne plume measurements and biological measurements on vegetation around the Unit #3 site, however, these phases of the program are not treated here in detail. In the following discussion, the instrumentation, methodology, and results for one typical day of intensive drift testing are presented together with the results of drift transport model calculations.

SOURCE DRIFT MEASUREMENTS

Cooling Tower Measurements

During intensive testing periods, drift measurements in the Chalk Point cooling tower are acquired via a suspended instrument package in a plane approximately 45 feet below the tower exit plane. Although drift measurements in other towers have been performed in the tower throat[3], an initial characterization study at Chalk Point determined that no decided advantage could be obtained by measuring in the throat. Ideally, the drift mass emission of a tower should be measured at the exit plane, however, the exit plane was ruled out because of the drastic influence of cross winds observed previously on updraft air profiles in natural draft towers[4].

The following instruments are included in the package for drift measurements:

1. The PILLS II-A (Particulate Instrumentation by Laser Light Scattering) electro-optical device for droplet size spectra determination.
2. The ESC Sensitive Paper (SP) droplet sizing system.
3. The ESC Heated Glass Bead IsoKinetic Sampling System (IK) for determination of drift mineral mass flux.
4. A Gill propeller anemometer for measurement of updraft air velocity from which droplet velocity is determined.

Grab samples of circulating water are also acquired during testing for chemical analysis for sodium and magnesium, the two cations which are present in the highest amounts in the water and which were chosen as tracer compounds for the IK measurements.

The drift instrumentation package is lifted to the measurement plane by two Shepard Niles hoists employed in the rigging system shown in

Figure 1. Measurements are performed along one diameter of the measurement plane at six points representing equal area segments.

In the measurements described here, data acquisition at each point lasted twenty minutes and yielded for that segment of the area represented by the measurement point, the liquid drift emission rate and its distribution over the droplet diameters. A summation of the emission parameters over all area segments yielded the total drift emission of the cooling tower. The IK system sampled continuously during the traverse and yielded the sodium and magnesium mineral flux at the measurement plane. Updraft air velocities were acquired and averaged for each point.

Stack Measurements

In addition to source measurements of drift acquired in the cooling tower, drift data was also acquired at the 400 foot level of Unit #3's 712 foot stack. Unit #3 employs a Peabody/Lurgi Radial scrubber system which utilizes brackish Patuxent River water for make-up just as the cooling tower does. Consequently, it was necessary to ascertain the nature of the stack drift emission level in order to judge its possible interference in the cooling tower study.

A Sensitive Paper device and an IK system were used to measure droplet flux and mineral mass flux respectively in an equal area traverse of two perpendicular diameters in the measurement plane of the stack. Updraft air velocity was acquired with an S-type pitot tube.

Source Results

The data which are presented here were acquired on one day of the Summer Seasonal Test, an intensive test which was conducted at Chalk Point from June 17 to June 24, 1976. On each day of the Seasonal Test a measurement traverse was performed in the cooling tower in conjunction with downwind ground-level measurements, meteorological data acquisition, airborne plume measurements and plume photography. A complete report of the Test has been submitted to the State of Maryland[5]. The source drift data chosen for presentation here were those acquired on June 22, 1976. These data are presented in Tables I through III and Figures 2 through 5. The data acquired on the other test days are similar in form to those shown here.
Table 1 shows the cooling tower drift mass emission as a function of droplet size. The cumulative per cent droplet mass emission below a certain size are plotted in Figure 2 along with data acquired from an older tower (Hornaing) in 1972 for comparison[3]. This figure shows that although larger droplets were measured in the Chalk Point tower, which could be associated with higher updraft air velocities measured there, the droplet mass median diameter for the tower is

smaller than that of the Hornaing tower. The differences between the two towers can best be compared in Figure 3 which plots cumulative drift fraction versus droplet size. The total drift fraction measured at Chalk Point for this day was .000565% versus a drift fraction of .0011% for the Hornaing tower. The Hornaing measurements were acquired similarly to those at Chalk Point via an instrument package traversing the throat of the 325 foot tower. Unfortunately, meteorological conditions during the measurements were not identical and hence may account, in part, for the differences observed in the droplet spectra. In fact, a more representative drift fraction for the Chalk Point tower would be the average from the entire Summer Seasonal Test which is .000717%.

Table II lists sodium and magnesium mass emission rates as measured by the IK system and as derived parameters, the sodium and magnesium mass emission fractions. The sodium mass emission fraction expresses the rate of sodium emission in per cent of the sodium circulating as solute in the basin water. The analogous definition holds for the magnesium mass emission fraction. Under the hypothesis that the concentration ratios of chemical elements are the same for drift droplets as for the circulating water, the sodium and magnesium mass emission fractions should be numerically equal for a diameter traverse. Table II shows that this hypothesis is confirmed by these test results and these results are typical of those observed on the other test days of the Summer Seasonal Test. Table II also contains averages of selected air and water circuit parameters acquired during the measurement period. It should be noted that the standard deviations of the measurement value fluctuations observed were, in general, higher than the measurement accuracy of the sensors indicating that the sensor accuracies were more than adequate for the purpose of these measurements.

The updraft air velocity and temperature profile acquired during the June 22 measurement traverse are shown in Figure 4 together with the time history of hot and cold water temperatures. The skewed velocity and temperature profiles are not atypical of data acquired on other days at Chalk Point and appear to result from influence of cross winds at the exit plane level of the tower.

The results of the stack drift measurements acquired on June 22 are shown in Figure 5 and Table III. When these data are compared with those acquired in the cooling tower it can be seen that the droplet mass median diameter of the stack is comparable to that of the cooling tower. Likewise, the sodium mineral mass emission is of the same order as that of the cooling tower. Consequently, the stack effluent can indeed act as an interference with any cooling tower modeling studies and its influence must be taken into account in the interpretation of downwind data acquired at Chalk Point.

GROUND LEVEL MEASUREMENTS

Concurrently with the drift data acquired in the cooling tower and scrubber stack, measurements for a number of drift parameters were made at ground level around the cooling tower. The primary objectives of these tests were: 1) to provide a quantitative analysis of the contribution of the cooling tower to ambient sodium depositions and sodium concentrations under various meteorological and plant operational conditions, and 2) to provide a data base for use in salt drift transport model verification and refinement.

Five fixed stations and one moveable station were employed for Airborne Particle Sampler (APS) determinations of sodium concentration. In addition, five mobile stations were used for measurements of airborne droplet and mineral concentration and deposition. These parameters and their associated methods of acquisition are listed in Table IV.

The deposition measurements specified in Table IV were conducted with samplers placed on the ground. The sodium mass deposition flux measurements employed a funnel and bottle assembly[5], while the droplet mass deposition flux measurements used sensitive paper disks fixed to a petri dish. The chemical analysis of the distilled water with which the funnel was rinsed enabled the determination of the sodium deposition flux (in $kg/km^2/mo$) for each of the mineral mass deposition samples. The liquid mass deposition flux data was obtained by counting the droplet stains on the sensitive papers, categorizing them, and converting the stain sizes to droplet sizes via calibration data. The information thus gained is a liquid mass deposition flux in kilograms of water per square kilometer per month.

The mineral and liquid mass concentration data were acquired using a tungsten mesh and a sensitive paper disk, respectively. Both of these sampling elements were mounted on a rotating arm which was fixed to a standard Airborne Particle Sampler supported by a surveyor's tripod. As with the deposition measurements, the mineral mass concentrations were based on the chemical analysis of the tungsten mesh for sodium, while the liquid mass concentrations were based on Sensitive Paper droplet stain counts.

The five mobile stations were located beneath the cooling tower plume. The fixed stations, as their name implies, would only receive cooling tower contributions if the wind were from the proper direction. The locations of all of these sampling stations used in the test on June 22 are shown in Figure 6 in relation to the Chalk Point cooling tower. Since a southerly wind was predominant during the test, stations 1S and MSW were upwind of the cooling tower, while the remaining stations were downwind of the tower and generally beneath the cooling tower plume.

Ground Level Measurement Results

A data summary sheet for this test is presented in Table V. The sampling elements and the units for the measured parameters are shown in this summary. An examination of the summary indicates that the most noticeable trend in this day's data is the decrease in liquid droplet deposition flux with distance from the cooling tower. There is also a general decrease in the sodium deposition flux and in the liquid droplet concentration with increasing distance downwind of the cooling tower. The sodium concentration data presented here indicate that the concentrations measured downwind of the cooling tower are not appreciably different from the upwind ambient levels on this day. The question of whether the naturally occurring fluctuations in measured ambient sodium concentrations are significant in comparison to those sodium levels contributed by the brackish water cooling tower will be examined in the data analysis phase of the program.

Following the summary table is Figure 7 which illustrates the results of the ground level droplet concentration and deposition measurements acquired via Sensitive Papers at Station 1 on June 22. The curves depict the percentage of total liquid mass concentration or deposition flux below a certain droplet size. It can be seen in the Figure that the mass median diameters of both the droplet concentration and deposition flux are in excess of 400 microns. Droplets with such large diameters are expected to reach ground level near the tower since they have large terminal velocities. It can also be seen that the deposition flux mass median diameter is larger than that for the concentration. In fact, it can be seen that any percentage of the liquid mass is composed of larger droplets for the deposition measurements than for the concentration measurements.

OTHER CHALK POINT FIELD DATA

In addition to the cooling tower source and downwind measurements acquired on this day, certain other data were acquired which play a role in meeting the objectives of the CPCTP. Meteorological data were acquired from a three-level tower located approximately one mile north of the cooling tower. These data are stored on magnetic tape and reduced at the ESC office to half hour averages of wind speed and direction, temperature, and dewpoint. During the source measurements, 35 mm plume photographic data was acquired at a position located along a line perpendicular to the path of the plume.

Photographs were acquired at two-minute intervals and the plume dimensions averaged over the measurement period resulting in an average plume geometry for that duration as shown in Figure 8. These data will eventually be employed in that phase of the program wherein visible plume model refinement is treated.

Additional data regarding cooling tower operational parameters were acquired during drift measurements. These included: hot, cold and make-up water temperatures respectively and updraft air wet- and dry-bulb temperatures. These data will be used in linking emissions to operational conditions once an adequate data base is established.

MODELING

In order to compare measured results with those predicted by drift transport models, the cooling tower source data and stack source data were used as inputs to two readily available models, the ESC/Schrecker model and the Israel-Overcamp model.

The ESC/Schrecker model is a salt drift model that takes the gravitational settling of the droplets, saline droplet evaporation, and dispersion of the droplets due to atmospheric turbulence into account. The meteorological parameters are incorporated as single time and space-averaged values of wind speed, temperature, relative humidity, and atmospheric stability. The model predicts the salt deposition flux, ground-level salt concentration, liquid water deposition flux, and ground-level liquid water concentration. The predicted values represent averages for a 22½° arc. The model does not calculate the vapor plume rise, but accepts the results of vapor plume models such as Slawson's or Brigg's. With minor additional efforts the vapor plume rise could be made an integral part of the model.

The Israel-Overcamp model which was developed for the CPCTP incorporates the same physical processes as the ESC/Schrecker model, and calculates the vapor plume rise in addition. The model predicts the center-line values of the salt deposition flux and the ground-level salt concentration. The available computer code of the model does not contain the calculations of liquid water deposition fluxes and liquid water concentrations. With relatively minor additions to the program these parameters could also be provided.

The input data for the two models were derived from the test data acquired on June 22, 1976, between 8:30 and 11:30. Table VI lists these input data.

Model calculations were carried out with both models for both the drift emission from the cooling tower and the stack. Table VII lists the model predictions as the sum of the contributions of each source for downwind distances that correspond to locations of monitoring stations.

The second column of Table VII lists the approximate time in per cent of the total test duration that each station was underneath the plume. These numbers were calculated from 10-minute averages of the wind direction as measured at the meteorological tower. As an example, Stations MSW and 1S did not stay underneath the plume at all and measured therefore ambient background data, while Station 1 remained 57.8% of the test time underneath the plume. The model predictions listed in Table VII take this time factor into account, i.e. if a station was underneath the plume 50% of the time, the model predictions for that station location were multiplied by 0.50. For convenience, the data of Table VII are also graphically presented in Figures 9 to 12.

When comparing the predictions of each of the models it should be recalled that the Israel-Overcamp model predicts center-line values, while the ESC/Schrecker model predicts averages for a 22½° arc. As a consequence the Israel-Overcamp predictions should be larger than those of the ESC/Schrecker model if all other things are equal.

Figure 9 depicts the measured sodium concentrations and the corresponding model predictions. The measured values represent the ambient sodium background, i.e. the sodium source contributions were not measureable on that day. Source contributions of less than 0.2 µg/m[3] as predicted by the ESC/Schrecker model are indeed not measureable in an ambient background that ranges from 0.3 to 0.5 µg/m[3]. The Israel-Overcamp model predicts measureable source contributions near to the sources but they represent center-line data and are thus too large considering actual plume movements which tend to distribute emissions over a sector.

Figure 10 shows the comparison of the sodium deposition predictions with measured data. The ambient sodium background was not measured on that day, but is estimated to be smaller than 20 $kg/km^2/mo$. The predictions show fair agreement with the measurements. Figures 11 and 12 depict comparisons between measured ground level droplet data and corresponding model predictions. The agreements are within a factor of three which is a good result considering the order-of-magnitude "accuracy" that is usually associated with drift transport model predictions.

The agreements between the presented model predictions and measured data are generally encouraging in light of the fact that none of these models, nor any other drift transport models, underwent any previous tuning. Model improvements through tuning is one phase of the CPCTP, and promising "raw" material that can be converted into a practical and tuned model is available.

CONCLUSIONS

A number of conclusions can be drawn from the data presented here. The drift measurements on the Chalk Point cooling tower showed a sodium mass emission fraction of .00068% of the sodium circulating as solute in the basin water. The drift fraction was .00057% of the circulating cooling water with a droplet mass median diameter of 76 μm.

These values can be compared with the average values observed during the entire Summer Seasonal Test (eight measurement runs) of .00090% for sodium mass emission fraction, .00072% for drift fraction, and 79 μm for droplet mass median diameter. These data indicate that this cooling tower provides good drift elimination compared with other natural draft towers on which drift measurements have been performed.

The Unit #3 stack drift data show drift droplet mass median diameter (127 μm) and sodium mass emission rate (.834 gm/sec versus .579 gm/sec for the cooling tower) comparable to that of the cooling tower thereby constituting a potential source of interference in downwind cooling tower drift measurements. The extent of this interference will be examined as the Project progresses.

The agreements between the presented model predictions and measured data are generally encouraging in light of the fact that none of these models underwent any previous tuning. The tuning of drift models is one phase of the program around which work is ongoing.

ACKNOWLEDGMENTS

The field measurements discussed above were performed as part of the Chalk Point Cooling Tower Project which is administered by the State of Maryland Department of Natural Resources, Dr. Richard Nietubicz, Administrator, CPCTP. The CPCTP is sponsored by the State of Maryland, the Electric Power Research Institute, Inc. (EPRI), the U. S. Energy Research and Development Administration (ERDA), and the Potomac Electric Power Company (PEPCO).

The authors wish to express their sincere appreciation to Mr. David Rutherford, Mr. Donald Cooke, and Mella Dillon for their assistance in preparing this paper.

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CHALK POINT COOLING TOWER PROJECT

TABLE I

DRIFT MASS EMISSION AS A FUNCTION OF DROPLET SIZE

Date and Time: June 22, 1976, 8:24 - 11:27 EDT
Measurement Mode: Equal Area Traverse
Measurement Location: North-South Diameter, Upper Level
Cooling Tower Cross-Sectional Area at the Measurement Location: 2050m²
These Data were Acquired by: PILLS and SP

I	d' µm	d" µm	Δd µm	d_c µm	ΔD gm/s	ΔD/D %
1	10	30	20	20	21.41	23.1
2	30	50	20	40	13.16	14.2
3	50	70	20	60	9.29	10.0
4	70	90	20	80	7.65	8.3
5	90	110	20	100	5.62	6.1
6	110	130	20	120	5.32	5.7
7	130	150	20	140	4.74	5.1
8	150	180	30	165	4.98	5.4
9	180	210	30	195	3.34	3.6
10	210	240	30	225	2.16	2.3
11	240	270	30	255	1.42	1.5
12	270	300	30	285	.91	1.0
13	300	350	50	325	1.19	1.3
14	350	400	50	375	.99	1.1
15	400	450	50	425	.87	.9
16	450	500	50	475	.80	.9
17	500	600	100	550	1.74	1.9
18	600	700	100	650	1.84	2.0
19	700	800	100	750	1.82	2.0
20	800	900	100	850	1.86	2.0
21	900	1000	100	950	1.48	1.6
22	1000	1100	100	1050	.04	.1
				D = ΣΔD =	92.63	100.1*

Mass Median Diameter: 76.4 µm

Drift Fraction: .000565% of design flow rate (984.1 m³/min)

* The summation of this column is not 100.0% due to rounding.

TABLE II

CHALK POINT UNIT #3 COOLING TOWER

Mineral Mass Emission

Date, Measurement Mode and Location Same as Table I.
These Data were Acquired by: Isokinetic Sampling System.

Measurement Time: 8:24 - 11:32 EDT
Sampled Air Volume: 19.7 m^3

Sodium Emission: .579 gm/s
Sodium Mass Fraction:[1] .00068 %

Magnesium Emission: .059 gm/s
Magnesium Mass Fraction:[1] .00068 %

Basin Water Concentrations

Sodium Concentrations: 5175 mg/liter
Magnesium Concentration: 535 mg/liter

Selected Cooling Tower Water and Air Circuit Parameters

The following data are averaged over the time period of the Equal Area Traverse:

Updraft air velocity:	4.6 m/s,	standard deviation:	1.21m/s
Wet bulb temperature:[2]	36.9°C ,	" " :	1.89°C
Dry bulb temperature:[2]	36.8°C ,	" " :	1.88°C
Hot water temperature:	44.0°C ,	" " :	.55°C
Cold water temperature:	30.8°C ,	" " :	.22°C
Makeup water temperature:	28.4°C ,	" " :	.41°C

[1] Mineral Mass Fractions are based on design water flow rate of 984.1 m^3/min (260,000 gpm)

[2] Wet- and dry-bulb temperature are identical within measurement accuracy.

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TABLE III

CHALK POINT UNIT #3 STACK

Mineral Mass Emissions at the 128 Meter Level.

Date and Time: June 22, 1976, 10:15 - 12:30 EDT
Measurement Mode as Above
Data was Acquired by: IK

Sodium emission: 0.834 gm/s
Magnesium emission: 0.098 gm/s

Gas Temperatures and Updraft Velocities at the 128 Meter Level.

The following data are averaged over the time period of the IK Equal Area Traverse:

Dry bulb temperature: 58.3°C, standard deviation: less than 1°C
Updraft velocity: 17.0 m/s, " " : not measured

Scrubber Water Concentrations

Sodium concentrations: 5687 mg/liter

Magnesium concentrations: 672 mg/liter

Scrubber Water Flow Rate: 0.862 m^3/sec (design)

TABLE IV

CHALK POINT GROUND LEVEL MEASUREMENT INSTRUMENTATION SUMMARY

	Parameter Measured	Sampling Element
1	Sodium Mass Concentration	Rotating Tungsten Mesh
2	Liquid Mass Concentration as a Function of Droplet Size	Rotating Sensitive Paper Disk
3	Liquid Mass Deposition Flux as a Function of Droplet Size	Stationary Sensitive Paper Disk
4	Sodium Mass Deposition Flux	Stationary Deposition Funnel

TABLE V

CHALK POINT GROUND LEVEL DATA SUMMARY

Date: June 22, 1976

Parameter Measured	Sodium Concentration	Liquid Droplet Concentration	Liquid Droplet Deposition Flux	Sodium Deposition Flux
Sampling Element	Tungsten Mesh	Sensitive Paper Disk	Sensitive Paper Disks	Funnel and Bottle Assembly
Units	μg/m³	μg/m³	kg/km²/mo	kg/km²/mo
Station				
1	0.55	11.5	91,300	502.
2	0.53	9.6	67,100	251.
3	0.48	8.7	68,500	28.8
4	0.44	11.2	38,900	123.
5	0.48	2.6	13,100	76.7

Additional Sodium Concentration Measurements Made with Tungsten Mesh

Station	1S	MSW	1NW	1NE	2NW	2NE
Sodium Conc. (μg/m³)	0.52	0.33	0.28	0.50	0.54	0.47

TABLE VI

Model Input Data

Source	Cooling Tower	Stack
Source Exit Height	124m	215m
Source Exit Diameter	54.9m	7.6m
Plume Efflux Velocity	4.6m/s	17m/s
Plume Exit Temperature	37°C	58°C
Circulating Water Salinity	1.32×10^{-2}	1.45×10^{-2}
Drift Droplet Mass Distribution	See Figure 2	See Figure 5
Ambient Temperature	23°C	
Ambient Relative Humidity	82%	
Atmospheric Stability	Pasquill C	
Ambient Wind Speed	3.6m/s	

Note: Both vapor plumes are assumed to be initially saturated. All drift droplets are assumed to have salt concentrations equal to that of the circulating water.

Table VII: Chalk Point Summer Seasonal Test - 6/22/76

Comparison of Measured Parameters to Transport Model Predictions

		Na Concentration $(\frac{\mu g}{m^3})$			Liquid Concentration $(\frac{\mu g}{m^3})$		Liquid Deposition kg/km²/mo		Na Deposition kg/km²/mo		
Sta. ID	% Time Under Plume	ESC Model	Israel Model	Measured (APS)	ESC Model	Measured (SP)	ESC Model	Measured (SP)	ESC Model	Israel Model	Measured (Funnel)
1	57.8	.0947	2.522	.554	14.2	11.5	111,670	91,300	749	20,411	502
MSW	0	.2189	4.895	.33							
2	57.8	.1436	3.098	.530	21.1	9.62	171,435	67,100	1095	3,554	251
3	46.5	.1800	0.744	.482	21.0	8.68	121,304	68,500	952	2,874	28.8
4	20.2	.0782	0.323	.436	9.1	11.2	52,696	38,900	413	1,248	123
5	57.8	.0594	0.110	.483	4.7	2.62	21,349	13,100	224	425	76.7
1NW	22.1	.0339	0.0003	.280					43	0.5	
1NE	27.9	.0428	0.0008	.50					54	0.8	
1S	0	0	0	.52					0	0	
2NW	46.9	.1700	0.0331	.54					62	29.6	
2NE	46.9	.1700	0.0331	.47					62	29.6	

* Measured values are source plus ambient - calculated values are the sum of tower and stack predictions

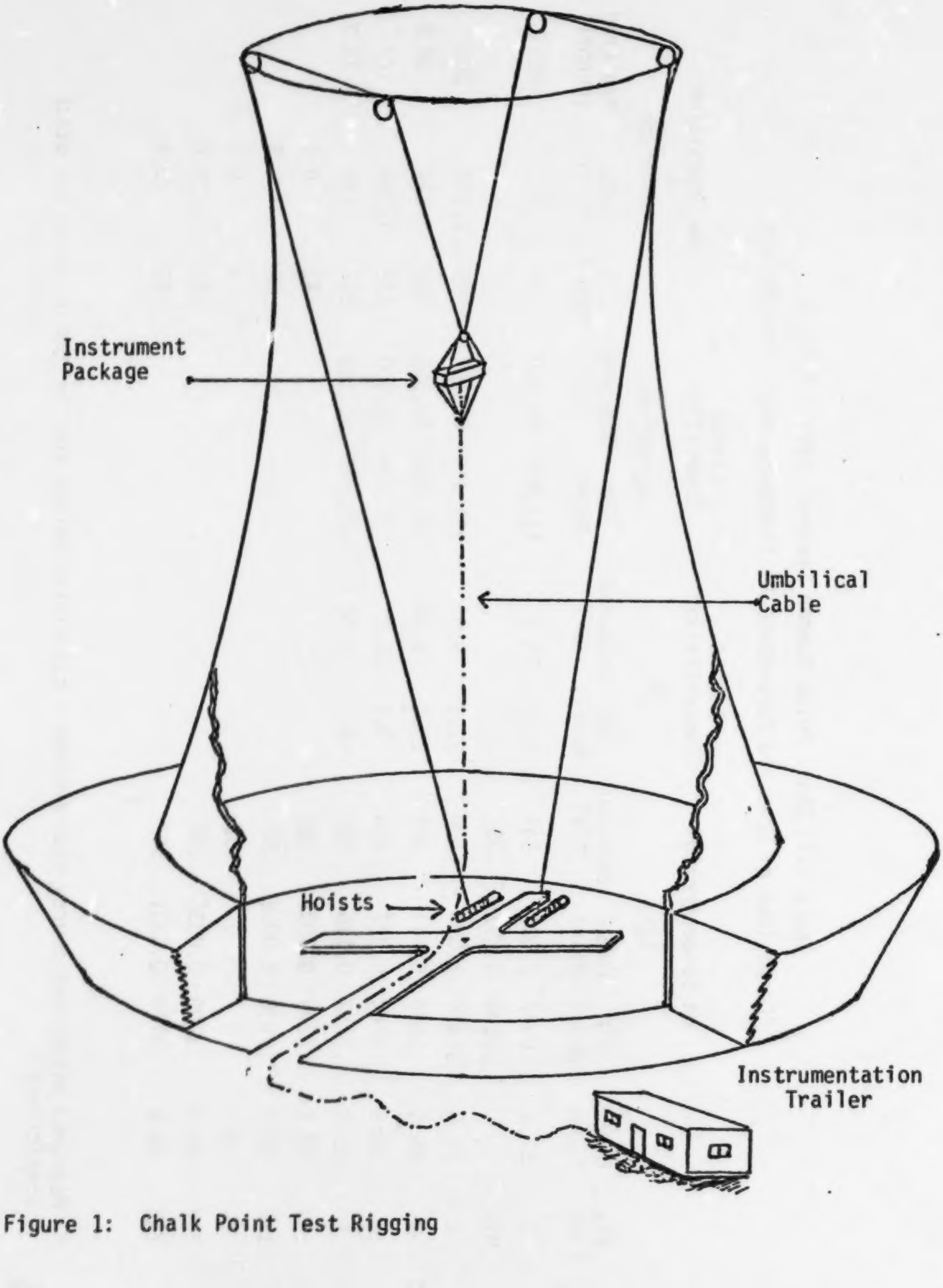

Instrument
Package
Umbilical
Cable
Hoists
Instrumentation
Trailer

Figure 1: Chalk Point Test Rigging

62<

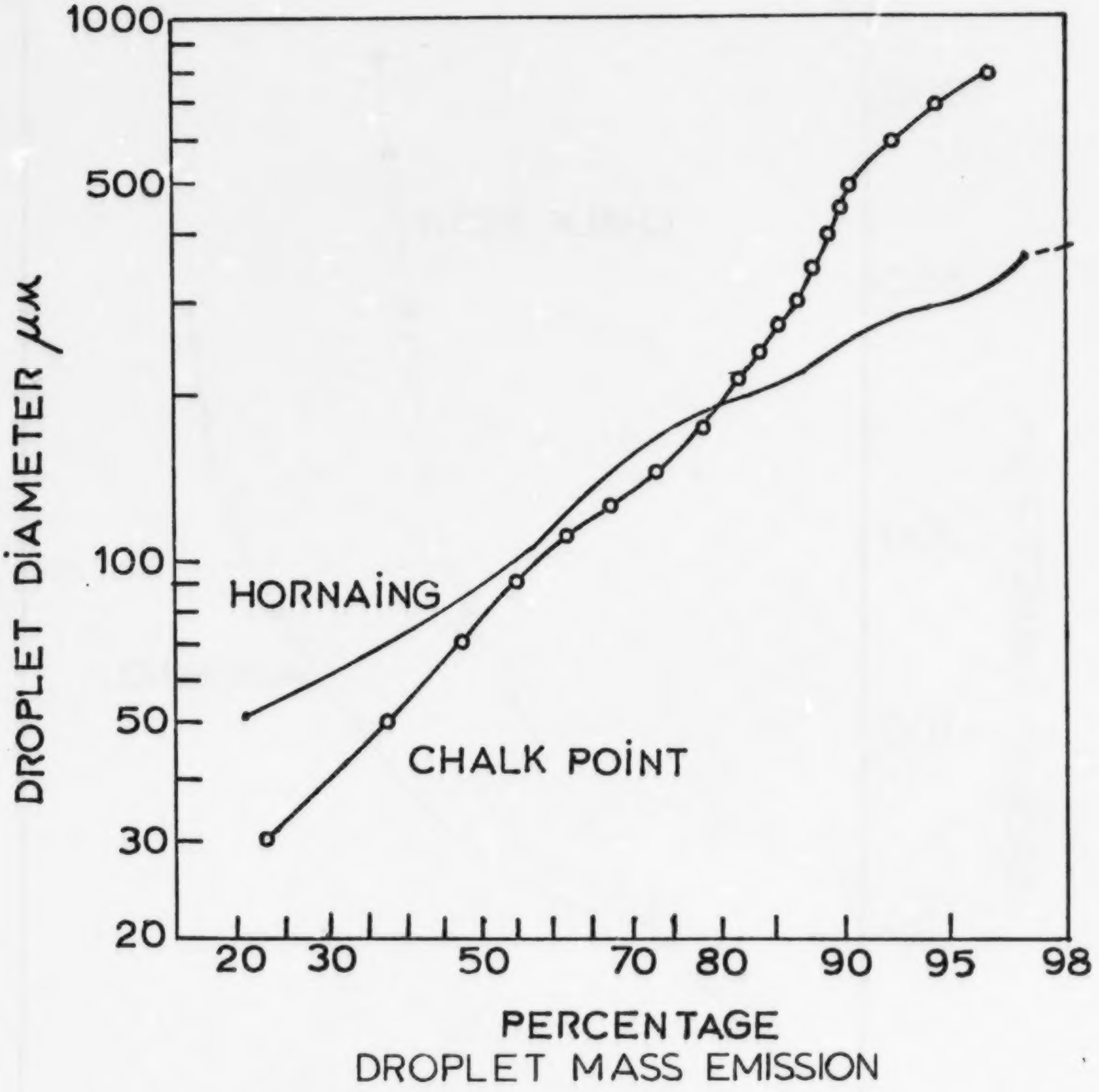


Figure 2: Comparison of Hornaing and Chalk Point Droplet Mass Emissions

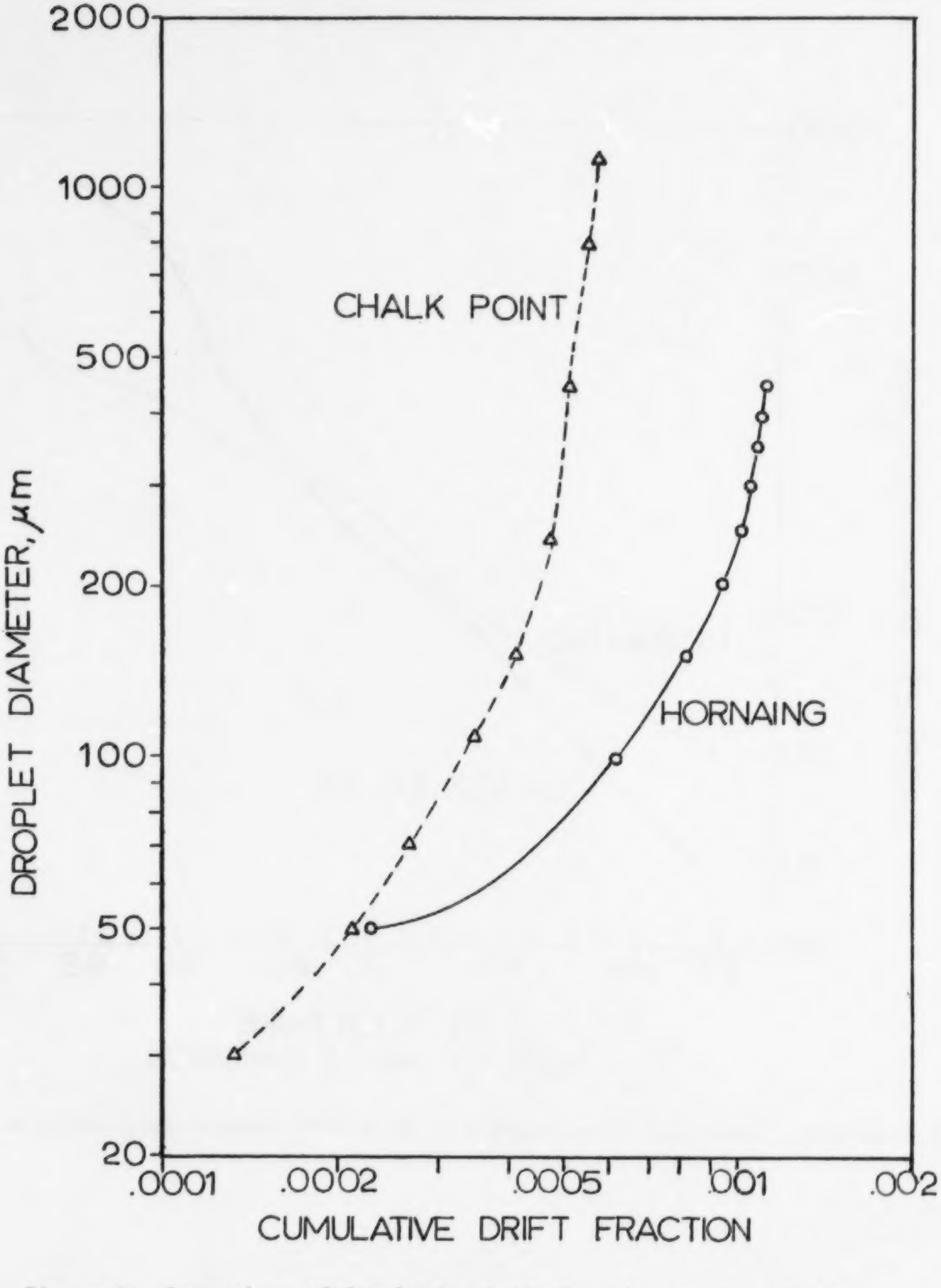


Figure 3: Comparison of Cumulative Drift Fraction versus Droplet Diameter for Chalk Point and Hornaing

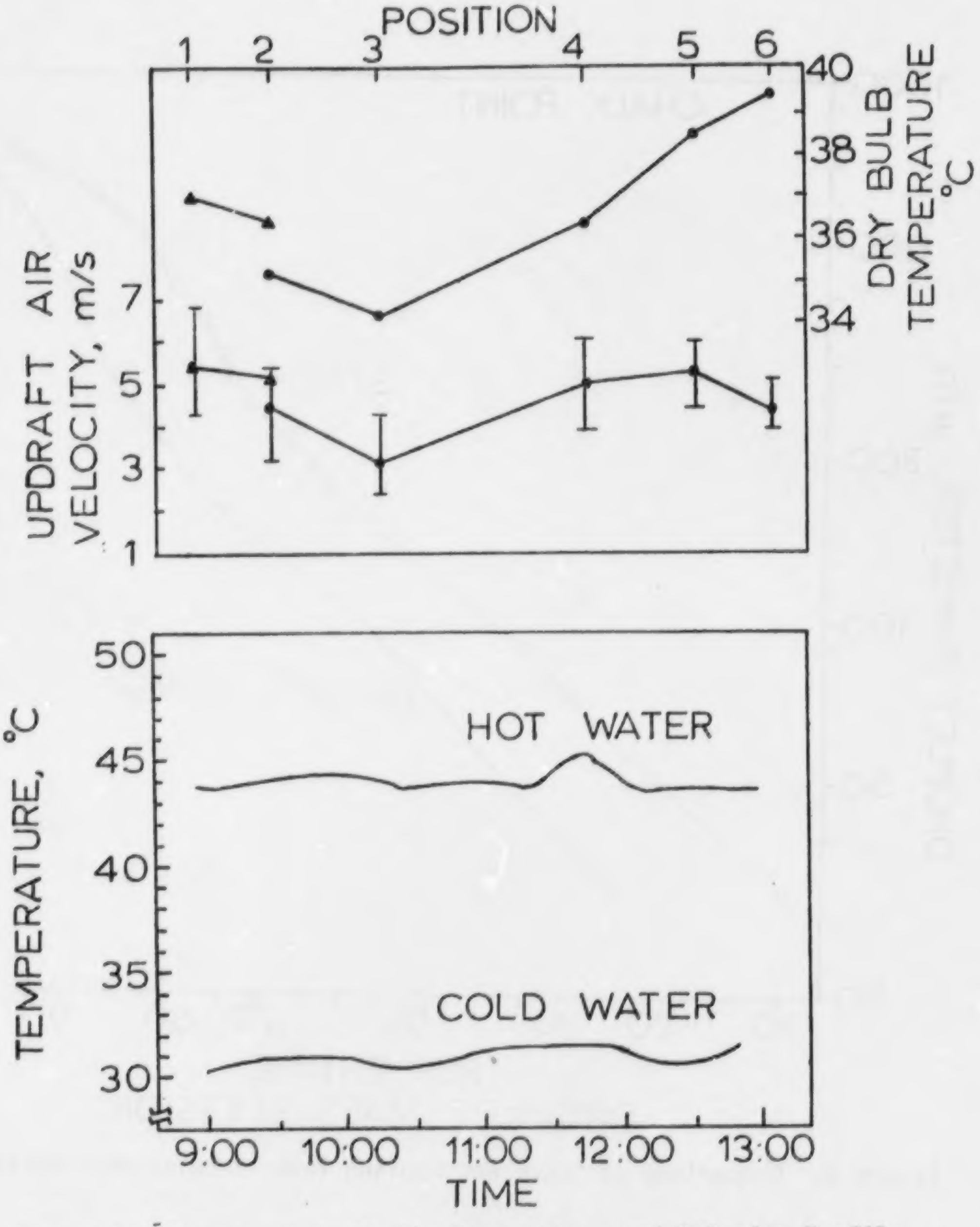


Figure 4: Above: Updraft Air Temperature and Velocity Profile for Chalk Point

Below: Time History of Hot and Cold Water Temperatures for June 22, 1976.

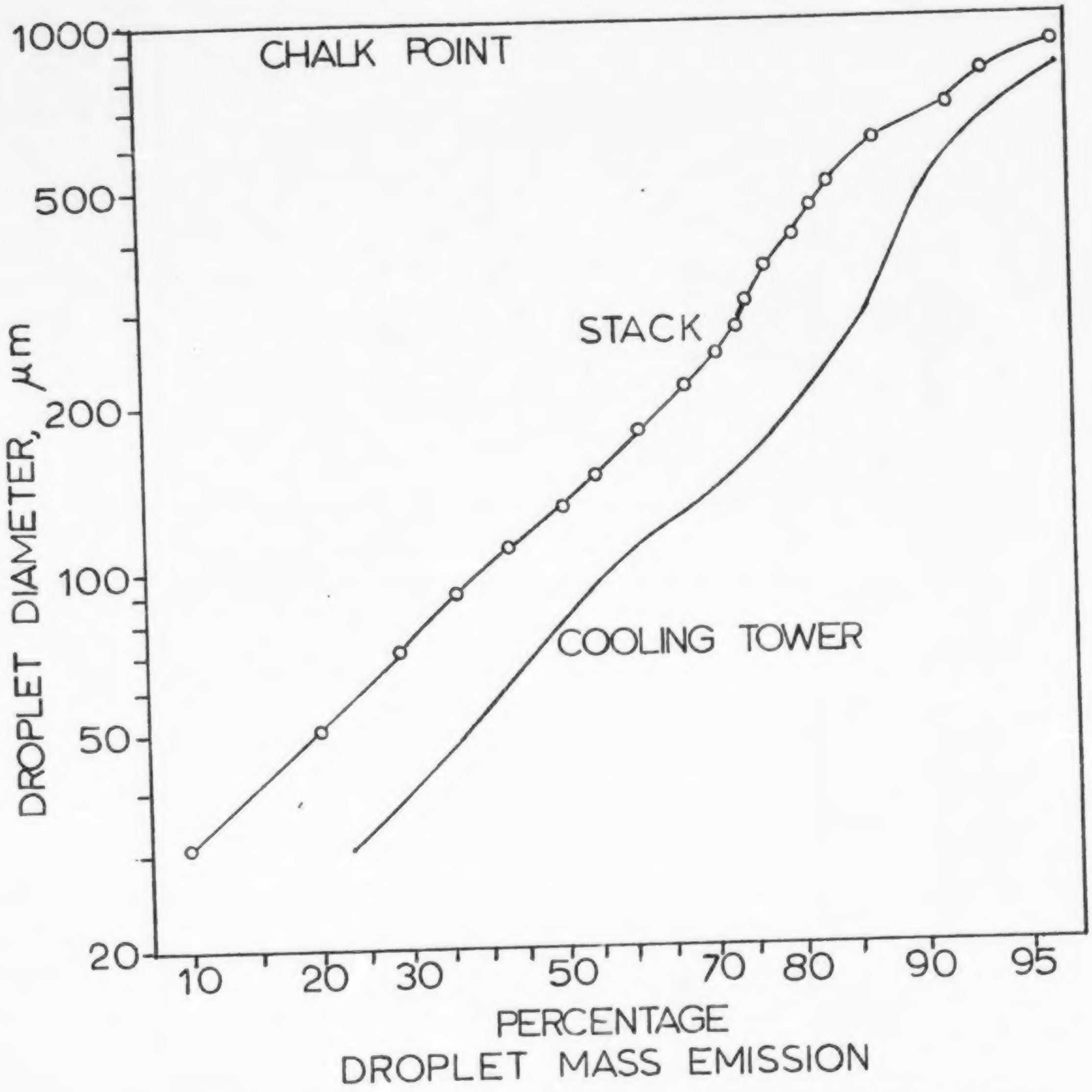
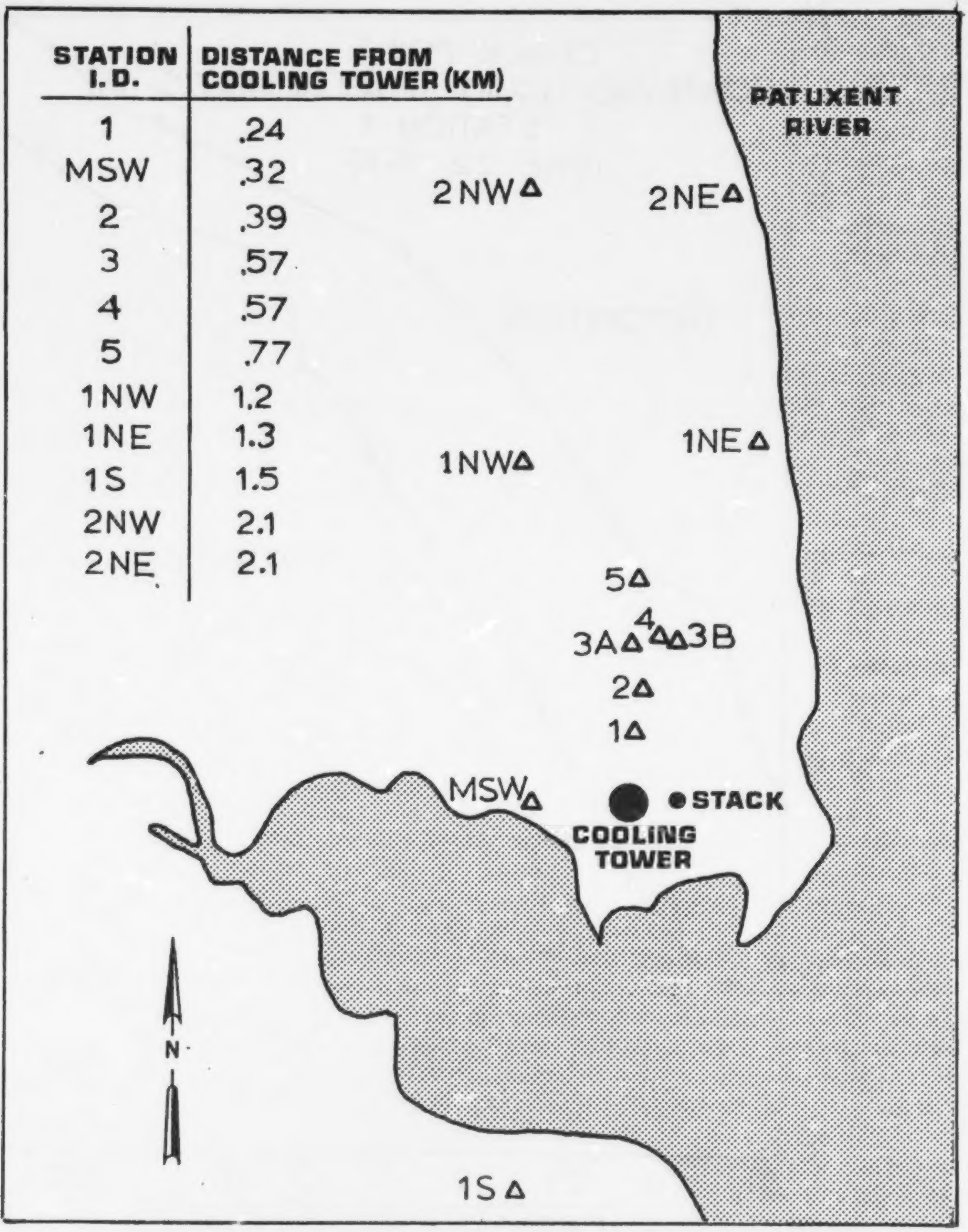


Figure 5: Comparison of Stack and Cooling Tower Droplet Mass Emissions



STATION I.D.	DISTANCE FROM COOLING TOWER (KM)
1	.24
MSW	.32
2	.39
3	.57
4	.57
5	.77
1NW	1.2
1NE	1.3
1S	1.5
2NW	2.1
2NE	2.1

PATUXENT RIVER
2NW
2NE
1NW
1NE
5
4
3A
3B
2
1
MSW
STACK
COOLING TOWER
N
1S

Figure 6: Chalk Point Ground Level Sampling Locations, June 22, 1976

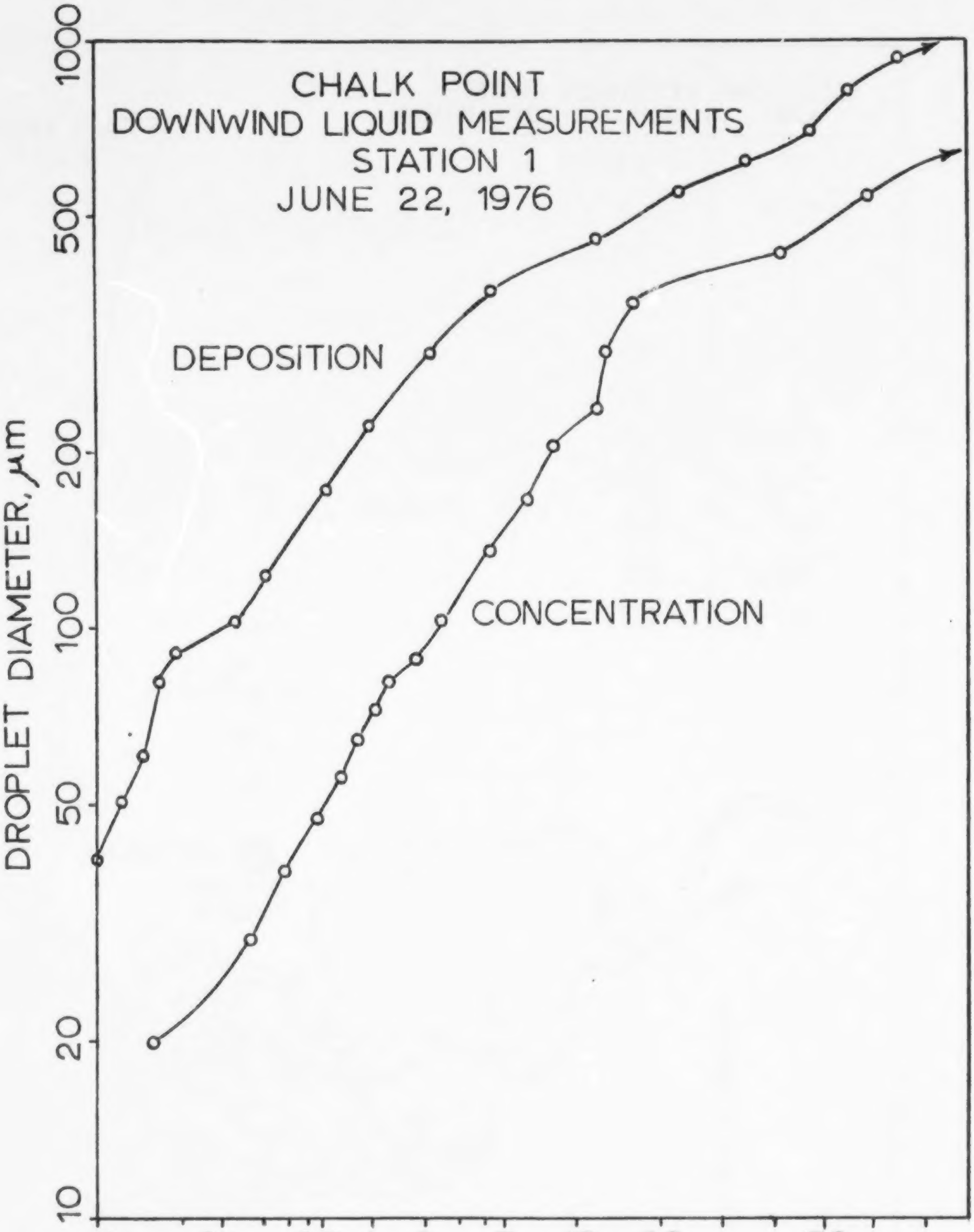


Figure 7: Comparison of Droplet Deposition and Droplet Number Concentration for Station One.

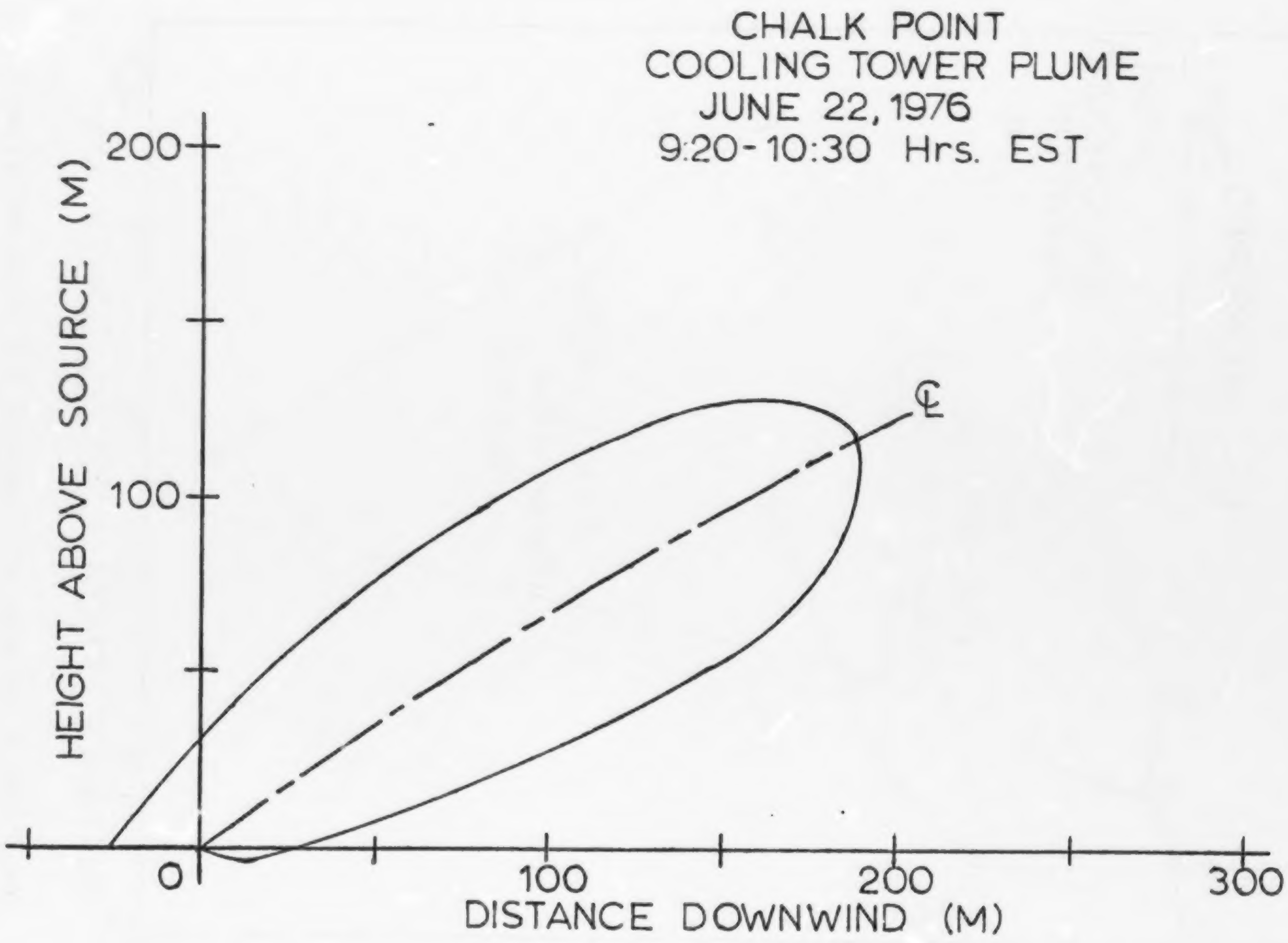


Figure 8: Chalk Point Cooling Tower Plume Profile and Center Line

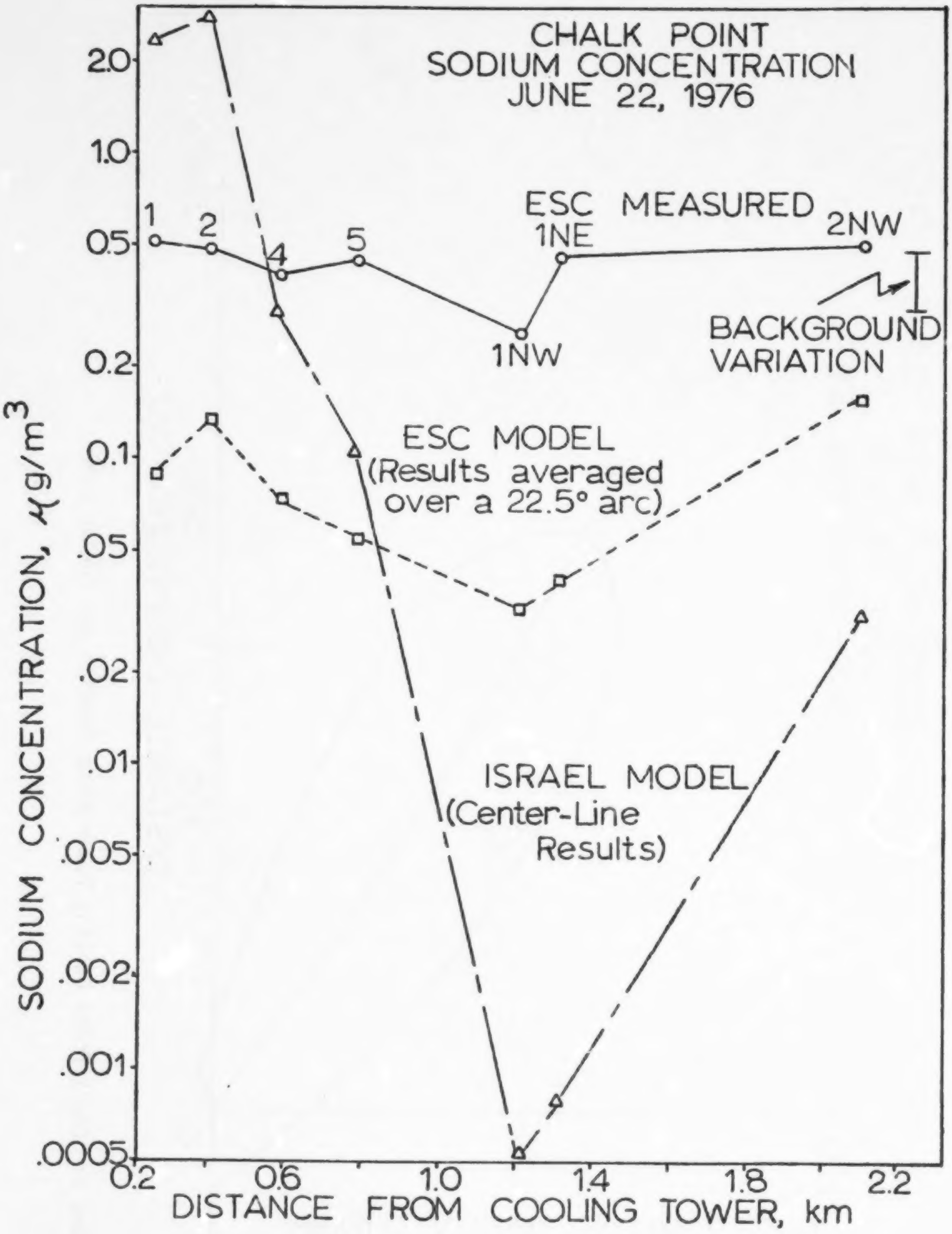


Figure 9: Comparison of Measured and Predicted Sodium Concentration Downwind of the Chalk Point Cooling Tower

ROW

70<

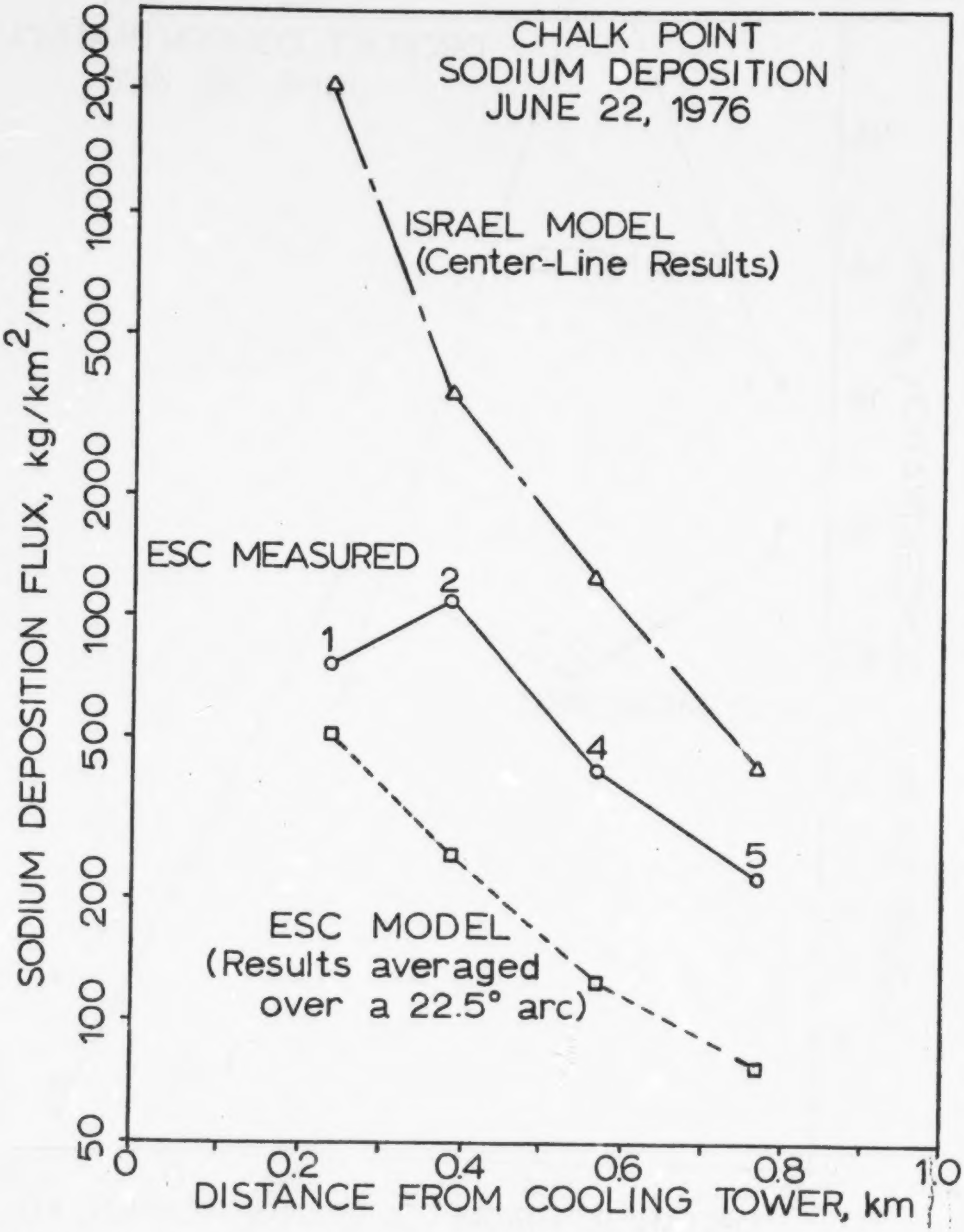


Figure 10: Comparison of Measured and Predicted Sodium Deposition Downwind of the Chalk Point Cooling Tower

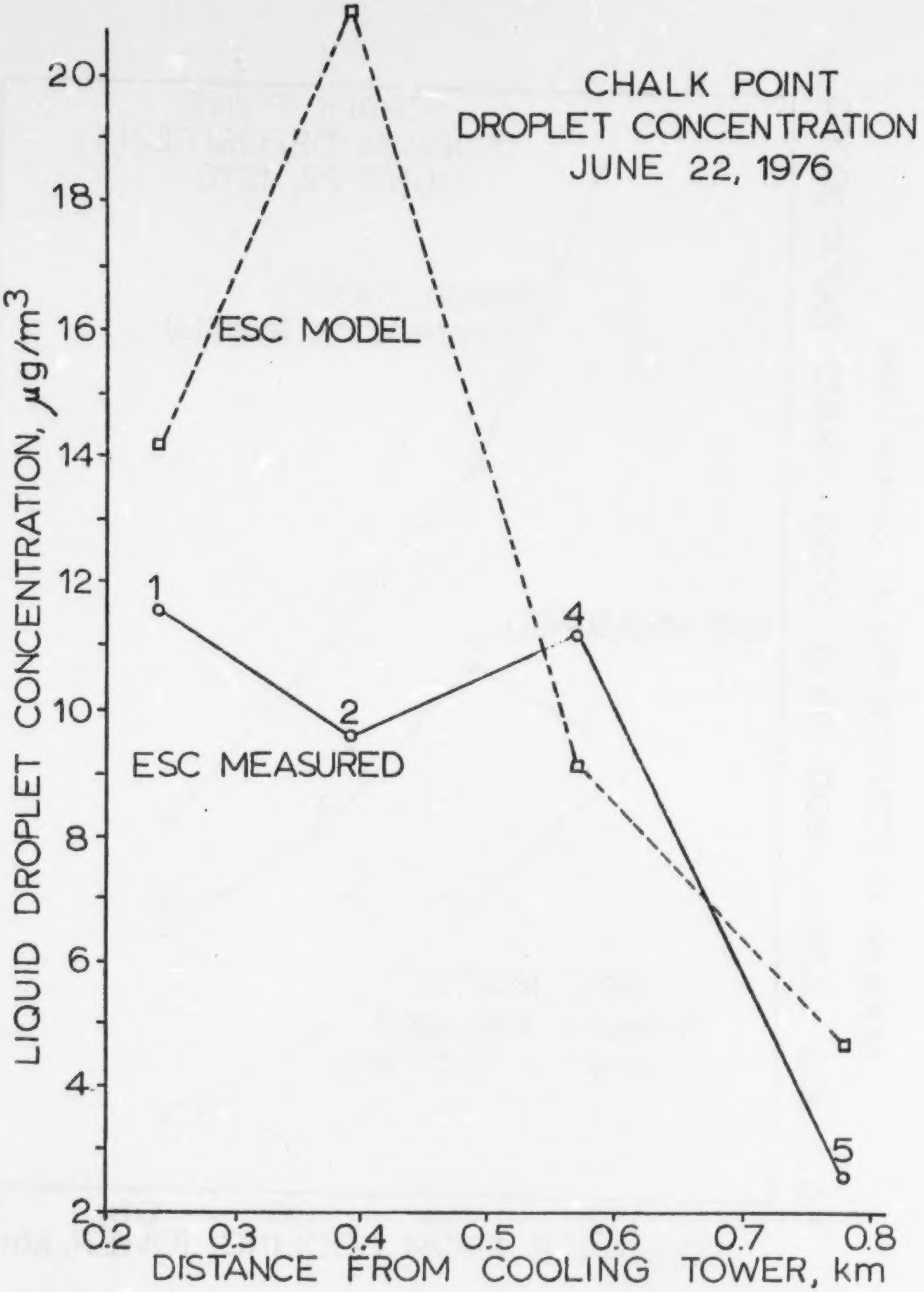


Figure 11: Comparison of Measured and Predicted Droplet Mass Concentration Downwind of the Chalk Point Cooling Tower

72<

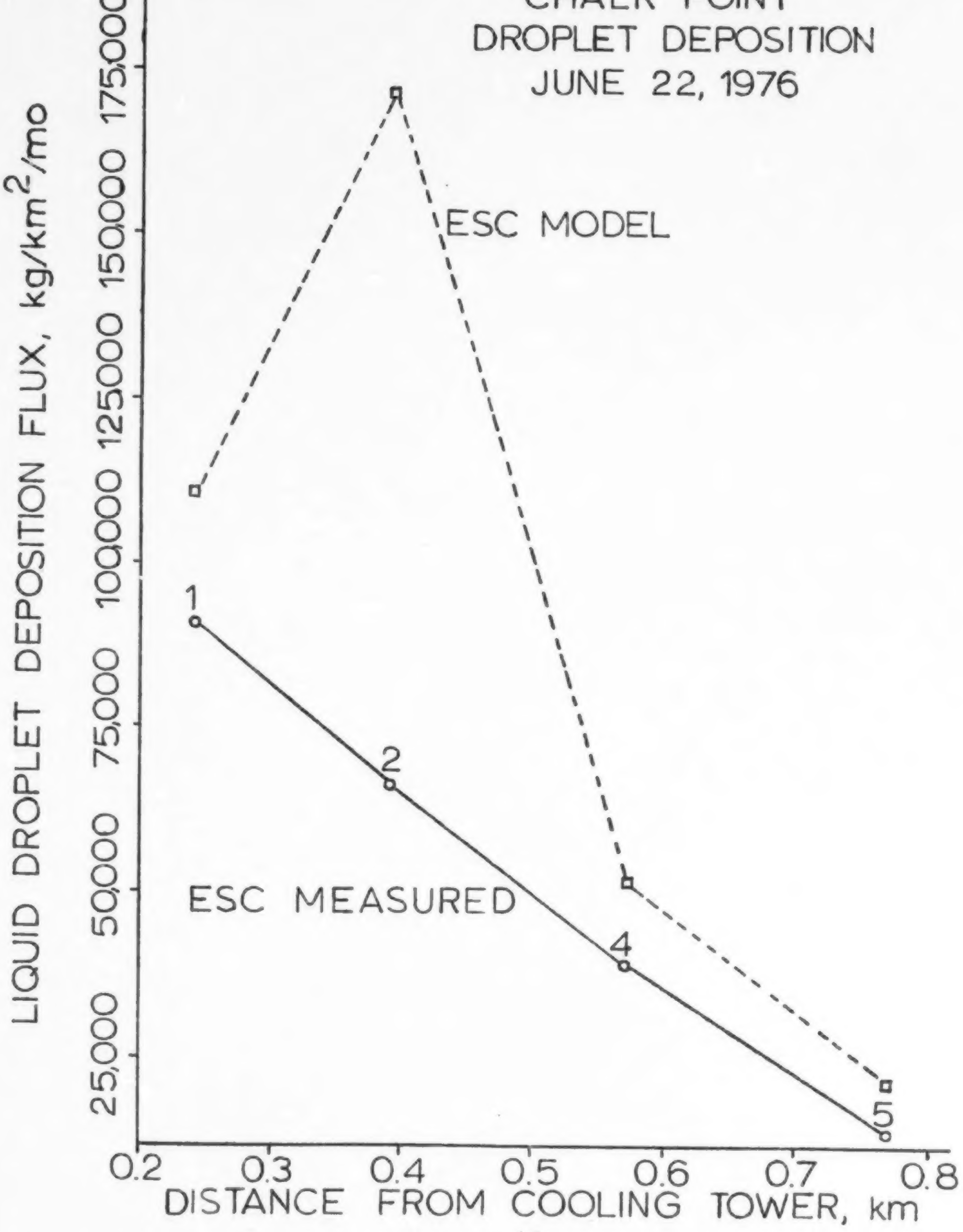


Figure 12: Comparison of Measured and Predicted Droplet Deposition Flux Downwind of the Chalk Point Cooling Tower

3-45-40

A SIMULATION OF WASTE HEAT UTILIZATION FOR GREENHOUSE CLIMATE CONTROL

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ABSTRACT

This study is concerned with simulating the use of waste heat for environmental control in a greenhouse structure. Consideration is given to the heat exchangers which may be used for this purpose, and detailed models have been developed to predict the performance of both dry (fin-and-tube) and wet (evaporative) exchangers. Comparative calculations have been performed, and the superiority of the evaporative exchanger has been demonstrated. A detailed model has also been developed for predicting thermal conditions within the greenhouse. The model allows for variations in greenhouse design (through changes in geometry, infiltration and construction materials) and ambient conditions (through changes in atmospheric temperature, wind speed and cloud coverage).

The foregoing models were combined to determine the coupled performance of a greenhouse-evaporative heat exchanger system. For specified control and interfacing conditions, the behavior of the combined system was evaluated by performing diurnal calculations for the Indianapolis, Indiana region and for representative days of each season. The calculations reveal that the evaporative heat exchanger can accomodate winter heat loads and that little care need be given to reducing greenhouse heat loss (allowing house construction costs to be minimized). It is also shown that, even for the high wet bulb temperatures associated with summer ambient conditions, effective summer cooling may be obtained with the evaporative system.

INTRODUCTION

Increasing energy costs and diminishing energy resources are providing strong stimuli for promoting energy conservation. For processes involving the conversion of thermal energy to work, conservation measures generally take the form of improving conversion efficiencies and/or utilizing the waste heat rejected by the conversion process. One process which has attracted considerable interest from the standpoint of waste heat utilization is that of electric power production in steam generating plants. However, the low temperature of the rejected heat generally restricts applications to the implementation of temperature control in commercially viable biological processes. Such processes include biological wastewater treatment, aquaculture, and the production of plants and animals in controlled enclosures. This study is concerned with the simulation of waste heat utilization for environmental control in such an enclosure.

In many regions of the world greenhouse agricultural production depends critically on artificial heating and cooling, and the use of powerplant waste heat represents a potential means of significantly reducing operating costs (Fig. 1). However, the capital investment required for coupling greenhouse operation to electric power production is large, and many uncertainties must be resolved before the necessary institutional arrangements can be made. One area of uncertainty concerns the heat demand of the greenhouse and the thermal performance of the associated heat exchangers. Reliable means must be developed for assessing these effects in order to predict, with confidence, greenhouse environmental conditions and waste heat requirements as a function of greenhouse design and seasonal and geographical variations.

Several such studies have been performed. Beall and Samuels [1] have analyzed the heat load and heat exchanger performance of a hypothetical greenhouse complex in Fort St. Vrain, Colorado, as part of a detailed economic study. However, the greenhouse size and construction were fixed and the heat loss was inferred from design curves which assume a linear dependence on ambient air temperature. Moreover, heat exchanger performance was assessed for only one heat exchanger type and size, operating under a single set of conditions. Trezak and Olszewski [2] also considered thermal problems related to waste heat utilization in a greenhouse structure. Although their study provided useful insights concerning system response as a function of site location and weather conditions, the related heat loss and heat exchanger calculations were highly approximate. A general assessment of the feasibility of waste heat utilization for greenhouse climate control has been made by Rimberg [3], but little information was provided which is pertinent to thermal system design and performance.

While the foregoing studies do much to suggest the feasibility of waste heat utilization for greenhouse climate control, they do not provide the means of optimizing system design for a specific site or heat source conditions. These means may only be provided by comprehensive models of the heat exchanger thermal performance and of the house heat load. In particular provision should be made for altering the heat exchanger size and/or geometry and for determining the electrical power required to circulate air through the exchanger. The models should also provide for determining the performance of the heat exchanger system as a function of operating conditions (corresponding to different outside air and condenser discharge temperatures). Moreover, the house heat load model should include provisions for varying house geometry and construction materials. It should also account for all factors which contribute to heat loss such as outside air temperature, wind speed, cloud cover and solar irradiance. Inclusion of such features necessitates a model for calculating heat loss on an hourly basis.

Comprehensive heat exchanger and greenhouse models have been developed in this study, and calculations have been performed to determine heat exchanger and greenhouse performance for climate conditions representative of the midwest.

HEAT EXCHANGER PERFORMANCE

The means by which heat is transferred from the condenser water to the desired load is crucial to any waste heat utilization scheme. Two different methods are considered in this study. They include the use of an indirect contact (dry) heat exchanger, as well as an evaporative (wet) heat exchanger. The primary advantage of the dry heat exchanger is that the air being heated does not experience a change in specific humidity. In contrast although the wet exchanger will saturate the air, it offers superior heat transfer characteristics by allowing for latent, as well as sensible, energy exchange.

The dry heat exchanger considered in this study is of the extended fin, cross flow configuration commonly used in air cooling and heating systems. The condenser water may make any number of passes through finned tubes, while air moves in cross flow over the tubes. Using standard procedures [4], a computer model of the system has been developed, with the details provided elsewhere [5]. The model provides the flexibility to vary the number of tube rows and passes, the length and diameter of the individual tubes, the fin arrangement, and the overall volume and frontal area of the exchanger. The required flow and geometrical parameters for a given core configuration are obtained from Kays and London [4], and calculations may be performed to determine the total heat transfer rate, and the outlet air and water temperatures as a function of the inlet temperatures and the air and water mass flow rates. Existing procedures [4] may also be used to determine the air-side pressure drop (which is needed to calculate fan power requirements) as a function of the core configuration and the air inlet conditions.

The wet heat exchanger considered in this study is a simple device which is commonly used for greenhouse cooling [6]. Water from the condenser is allowed to flow vertically down a pad of crushed aspen fiber, while air is blown horizontally across the face of the pad. Although the analysis of this system is handicapped by the absence of detailed empirical information, reasonable estimates may be made by using procedures suggested by Beall and Samuels [1]. Although their study was essentially qualitative in nature, some data concerning the heat transfer and pressure loss characteristics of the pad were obtained.

The thermal analysis of this study is based upon dividing the pad into a network of finite elements (Fig. 2). Since air and water properties are invariant in the direction normal to the air and water flow (x_w), the problem may be treated as two-dimensional in y_w and z_w. Note that a variable grid size is used in the interest of accuracy, with smaller grids employed at the top of the pad where the air-water temperature difference is largest. Energy and mass balances of the following form may then be applied to each of the elements. The rate of energy transfer from the water flowing through an element may be expressed as

$$d\dot{q}_w = d(\dot{m}_{w,e}c_{p,w}T_w) \tag{1}$$

and it must be equivalent to the rate of energy transfer to the air. This transfer may be expressed as the sum of two components

$$d\dot{q}_a = d\dot{q}_{a,s} + d\dot{q}_{a,\ell} \tag{2}$$

where

$$d\dot{q}_{a,s} = \dot{m}_{a,e}c_{p,a}dT_a = h(T_w - T_a)dA_{ht} \tag{3}$$

and

$$d\dot{q}_{a,\ell} = h_{fg}\dot{m}_{a,e}d\omega_a \tag{4}$$

where

$$\dot{m}_{a,e}d\omega_a = k_d[\omega_{a,s}(T_w) - \omega_a]dA_{ht} \tag{5}$$

The convection transfer coefficients are evaluated from correlations for a packed bed of small diameter cylinders [7]. Use of these correlations for the evaporative pad has been suggested by Beall and Samuels [1], and they are of the form

$$j_1 = C\,Re_a^n \tag{6}$$

where

$$Re_a < 120: \quad C = 1.650, \; n = -0.507 \tag{7}$$

$$Re_a > 120: \quad C = 0.687, \; n = -0.237 \tag{8}$$

and

$$j_2 = 0.929 j_1 \tag{9}$$

The j factors are related to the convection coefficients by expressions of the form

$$j_1 = \frac{h}{\rho_a c_{p,a} \bar{V}_a} Pr_a^{2/3} \tag{10}$$

$$j_2 = \frac{k_d}{\rho_a \bar{V}_a} \left(\frac{p_{a,m}}{p_t}\right) Sc_a^{2/3} \tag{11}$$

and the Reynolds number is defined in terms of the fiber diameter ($Re_a = \bar{V}_a d_f/\nu_a$). Approximate average values of d_f and the heat transfer area per unit volume ($\alpha \equiv A_{ht}/V$) have been measured by Beall and Samuels [1] for the pad material. The velocity of the air in the pad is expressed as

$$\bar{V}_a = \frac{\dot{m}_a}{\rho_a x_w y_w} \tag{12}$$

and the total pressure is assumed constant at 10^5 N m^{-2}. Procedures for evaluating the mean dry air pressure are discussed elsewhere [5].

Equations (1) to (5) may be integrated to obtain the amounts by which T_a, T_w and ω_a change for a given element [5]. The results may then be used in a marching solution which proceeds sequentially from element to element along a horizontal row with the air flow and from row to row with the water flow [5]. The final solution yields the air and water outlet temperatures, the air outlet specific humidity, and the total heat transfer and evaporation rate for the pad.

The procedures of Kays and London [4] were also used to determine the pressure drop of air flowing through the evaporative pad. However, since the friction factor f and the hydraulic radius r_h required for the calculations are unknown for the packing material, they had to be synthesized from peripheral data. This was done by extrapolating f and r_h data available for loosely packed wire matrices of large wire diameter [4].

In particular it was found that this data could be correlated in terms of α [5]. Hence, if the evaporative pad is modeled as a wire screen matrix, the correlations may be used to obtain values of f and r_h corresponding to the value of α which is representative of the tightly packed, small diameter pad fibers. The friction factor results are of the form

$$\begin{aligned} f &= 51.4\ Re^{-1.0} \qquad (Re < 100) \\ f &= 2.046\ Re^{-0.3} \qquad (Re \geq 100) \end{aligned} \tag{13}$$

where $Re = 4r_h\ G/\mu$, and the hydraulic radius is $r_h = 0.0022$ m. These results are compatible with the single pressure drop measurement reported for the evaporative pad [1].

Since the typical greenhouse air handling system of Fig. 3 results in negligible pressure losses in the return header (the attic), the pressure drop imposed by the heat exchanger provides the dominant power requirements for the air system. With the facility to determine this pressure drop, the power requirement may then be found from standard procedures [5]. In this study the airflow was assumed to be maintained by a typical centrifugal fan, and from available performance curves [8] the power requirement may be determined as a function of air flowrate and inlet conditions.

The foregoing procedures have been used to evaluate the performance of the extended fin and evaporative heat exchangers. To make a meaningful comparison between the two kinds of exchangers, it is necessary to specify dimensions which are appropriate to the greenhouse application. In this study the evaporative pad is assumed to be installed along an entire greenhouse wall which is 150 m long. It is also assumed to be 2 m high and 0.05 m deep ($x_w = 150$ m, $y_w = 2$ m and $z_w = 0.05$ m). Although the low acquisition costs of the evaporative pad permit such a large system ($A_{fr} = 2\ \text{m} \times 150\ \text{m} = 300\ \text{m}^2$), the size of the extended fin heat exchanger is severely limited by cost. For this study a frontal area of $A_{fr} = 2\ \text{m}^2$ was assumed to be appropriate for the dry heat exchanger.

In comparing the wet and dry heat exchangers, it is important to be cognizant of the fluid outlet temperature extremes. For the dry heat exchanger the exit water temperature may not be less than the air inlet temperature, and the exit air temperature cannot exceed the water inlet temperature. For the evaporative pad, the exit air temperature cannot exceed the water inlet temperature, and the temperature of the exit water may not drop below the wet bulb temperature of the inlet air.

The effect of air mass flow rate on the fluid outlet temperatures is shown in Fig. 4 for representative inlet temperatures. From the standpoint of heating the air, it is obviously desired to use the dry heat exchanger with a reduced air flow rate. The wet heat exchanger is less effective in heating the air due to the evaporative cooling mechanism. However, because of this mechanism, condenser water cooling is substantially more significant for the wet heat exchanger. In fact for an air flow rate in excess of 70 kg s^{-1}, both the air and the water experience cooling. The effect of varying the water mass flow rate is shown in Fig. 5, and from the standpoint of increasing the air outlet temperature, it is obvious that a large flow rate is desirable. However, increasing the value of $\dot{m}_w$ also diminishes the condenser water cooling. Maximum condenser water cooling is obtained for the evaporative exchanger with $\dot{m}_w \leq 15$ kg s^{-1} and/or $\dot{m}_a \geq 75$ kg s^{-1}, in which case $T_{w,out}$ is equal to the wet bulb temperature of the inlet air.

Note that the foregoing results pertain to dry inlet air (RH=0), and any increase in humidity would diminish the evaporative cooling effect. This trend is shown in Fig. 6, where $T_{a,out}$ is plotted as a function of $\dot{m}_a$. The largest value of $T_{a,out}$ for the wet exchanger corresponds to saturated inlet air, and for this case $T_{a,out}$ simply approaches $T_{a,in}$ with increasing $\dot{m}_a$. The low value of $T_{a,out}$ associated with dry inlet air conditions suggests the potential of using the evaporative pad to cool greenhouse air during the summer, while simultaneously cooling the condenser water. However, the degree to which the air is cooled diminishes with increasing RH, and there is no cooling when the inlet air is saturated.

The heat exchanger transfer rate determines the condenser cooling load which may be assumed by the exchanger, and its dependence on air mass flow rate is shown in Fig. 7. The higher rate associated with the evaporative exchanger is due to the latent heat transfer effect, and the asymptote which is approached with increasing $\dot{m}_a$ is due to the fact that the water outlet temperature approaches its extreme value.

Any comparison of heat exchanger performance should also be based on associated air power requirements, and results are presented in Fig. 8. Because of the much smaller value of A_{fr}, which provides for a much larger air velocity in the exchanger core, the power requirement of the dry exchanger is two to three orders of magnitude larger than that of the evaporative pad. Combining the thermal performance and the fan power requirements as a power ratio, q_{hx}/P_a, the effect of frontal area on this ratio is shown in Fig. 9. Operating with $A_{fr} = 300$ m^2 for the evaporative pad, a ratio in excess of 10^4 may be achieved. For the dry exchanger larger ratios are possible for an equivalent value of A_{fr}. However the initial costs associated with this heat exchanger preclude the use of such an area, and it is doubtful that a ratio in excess of 100 could be achieved. Note that the value of $\dot{q}_{hx}/P_a$ increases with decreasing $T_{a,in}$ for the dry exchanger, and it increases with decreasing $T_{a,in}$ and RH for the evaporative pad.

Its higher heat dissipation rate, lower operating power and acquisition costs, and its potential for use in summer cooling renders the evaporative pad preferable to the extended-fin heat exchanger as the primary heat source for the greenhouse. All subsequent considerations are therefore based on the use of such a pad.

GREENHOUSE CONSTRUCTION AND ENERGY BALANCE

The waste heat requirements of the greenhouse depend on the net heat exchange between the greenhouse atmosphere and the external environment. This heat exchange, in turn, depends on the greenhouse design and construction. A significant feature of the present analysis is that it allows for the systematic variation of parameters such as the greenhouse wall dimensions and materials, the number of gables in the roof, and the gable tilt angle. It therefore provides some basis for optimizing the greenhouse design. The basic greenhouse configuration is shown in Fig. 10. However, although the house is multigabled, it may be modeled as if it had only six surfaces (Fig. 11). This simplification is appropriate, so long as the model accounts for the wall surface areas, sun shading effects and radiative view factors associated with the actual greenhouse.

The energy (and mass) exchange mechanisms relevant to the greenhouse are shown in Fig. 12. Energy may be transferred to exterior surfaces of the walls by convection, $\dot{q}_{co}$, solar radiation, $\dot{q}_{sol,b}$, and by thermal radiation exchange with the atmosphere and the ground, $\dot{q}_{tr}$. Energy transfer to the interior surface occurs by convection from the greenhouse air. Moreover, energy transfer to the greenhouse air may occur via the heat exchanger and, indirectly, via solar radiation transmitted by the greenhouse glass. It should be noted that greenhouse thermal conditions are also influenced by air infiltration effects. The term infiltration is used to characterize air leakage due to structural deficiencies, as well as ambient air which is purposely introduced to the greenhouse (through adjustable louvers) to maximize condenser cooling effects and to satisfy crop respiration requirements. A comprehensive model of this system has been developed, and its key features are outlined in the following paragraphs. Additional details are provided elsewhere [5].

An energy balance may be performed for each of the greenhouse walls, and assuming the wall heat capacity to be negligible (which is reasonable for the typical thin-wall greenhouse construction), this balance simply requires that

$$\dot{q}_{co} + \dot{q}_{tr} + \dot{q}_{sol,b} + \dot{q}_{ci} = 0 \qquad (14)$$

where heat transfer to the wall is designated to be positive. The external convection transfer rate $\dot{q}_{co}$ is determined from an appropriate correlation [9], and the thermal radiation term $\dot{q}_{tr}$ is determined from detailed consideration of the radiation exchange between the exterior wall and the surroundings. The analysis accounts for irradiation of the wall due to atmospheric and ground emission, and it includes all of the appropriate geometric quantities, such as the wall surface areas and view factors [5].

The solar radiation absorbed by the wall is determined from an analysis which systematically treats the atmospheric attenuation of this radiation and the effect of its directional and spectral characteristics. The analysis provides for determination of the direct and diffuse contributions to the total insolation and for the effect of wall orientation, geographic location, and the solar angles (azimuth, altitude, hour and declination) on the incidence angle of the direct component. The analysis also accounts for the fact that sections of the roof may be shaded by adjoining gables and that vertical walls may be shaded by adjoining houses.

If the wall material is glass, approximately 3% of the insolation is absorbed [9,10], with the remainder being reflected and transmitted. Reflection of the direct radiation was determined from standard procedures involving application of Snell's law and the Fresnel equations to the air-glass interfaces [11], and reflection of the diffuse radiation was determined by integrating the directional reflectivity over the field of view [12]. The transmitted radiation was then obtained by subtracting the absorbed and reflected components from the insolation. There is, of course, no transmission if the wall is constructed from an opaque material such as wood. In this case the absorbed solar radiation may readily be determined from known values of the material absorptivity.

The inside convective heat transfer $\dot{q}_{ci}$ may include both latent and sensible contributions. The latent contribution is due to condensation which would occur on the interior surface of the wall, if T_{bi} were less than the inside air dew point temperature. In this study it is assumed that, if condensation occurs, a thin film of water forms on the inside surface and the condensation rate is determined by vapor transport in the concentration boundary layer adjoining the film. If it is further assumed that the concentration boundary layer is analogous to the free convection thermal boundary layer and that the Lewis number is unity, the heat transfer rate may be expressed as [8]

$$\dot{q}_{ci} = k_d A_b (i_{ai} - i_{bi}) \tag{15}$$

where the moist air enthalpy i is defined as

$$i = c_p T + h_{fg} \omega \tag{16}$$

The convection mass transfer coefficient is related to the convection heat transfer coefficient h_i ($h_i = k_d c_p$), which may be assigned a value characteristic of free convection.

For prescribed climatic and inside air conditions, equation (14) may be used with Fourier's law for conduction heat transfer through the wall to determine the values of T_{bi} and T_{bo}. These temperatures may then be used to determine the net heat transfer to or from the wall.

The transient thermal response of the greenhouse air may now be determined by writing an energy balance for the air. The heat gain or loss sustained by the house includes both latent and sensible energies, and through an extensive development [5] the balance may be shown to be of the form

$$m_{ai} \frac{di_{ai}}{dt} = \dot{m}_{a,inf} (i_{ao} - i_{ai}) + \dot{q}_{sol} + \dot{q}_{hx} + \dot{q}_{bi} \tag{17}$$

where m_{ai} is the greenhouse air mass. The term $\dot{q}_{sol}$ is the rate at which solar energy is transmitted through the glass walls, and $\dot{q}_{hx}$ provides the rate at which heat is added by the evaporative pad. The heat transfer rate through the walls may be expressed as

$$\dot{q}_{bi} = - \sum_{i=1}^{6} \dot{q}_{ci} \tag{18}$$

where $\dot{q}_{ci}$ is given by equation (15). The variation of the inside air enthalpy with time may then be determined by integrating equation (17) and iteratively solving the result with equation (14).

The variation of the air specific humidity with time may be obtained by integrating a species balance of the form [5]

$$\frac{d\omega_{ai}}{dt} = \frac{1}{m_{ai}}[\dot{m}_a(\omega_{a,out} - \omega_{a,in}) + \dot{m}_{a,inf}(\omega_{ao} - \omega_{ai}) - \sum_{i=1}^{6} k_d(\omega_{ai} - \omega_{bi})A_b + \dot{m}_{w,ev}] \qquad (19)$$

The first and second terms on the right-hand side of this expression account for moisture addition via air flow through the evaporative pad and via the infiltration, respectively. The third term accounts for the effect of condensation on the walls, and the last term accounts for evaporation from the greenhouse soil and plants. Assuming that half the solar radiation entering the greenhouse energizes this evaporation [1], $\dot{m}_{w,ev}$ may be approximated as 0.5 $\dot{q}_{sol}/h_{fg}$. Obtaining i_{ai} and ω_{ai} from equations (17) and (19), respectively, the greenhouse air temperature T_{ai} may then be determined from equation (16).

To test the foregoing transient model, calculations were performed to determine the response of the greenhouse temperature to the initiation of heating, Fig. 13, and to a diurnal climatic variation with no heating, Fig. 14. For these calculations, as well as those presented in the following section, a greenhouse design is assumed for which

$L = 150$ m $W = 30$ m

$H = 3$ m $\beta = 0.35$ rad (20°)

Moreover, all walls except 1 and 2 are assumed to be glass. For the heating transient it is also assumed that the infiltration rate is $\dot{m}_{a,inf} = 30$ kg s^{-1}, the ambient air is still, and there is no solar radiation. From Fig. 13 it is evident that, with the heat exchanger delivering 2 MW, the greenhouse air may be heated from 0°C to a satisfactory steady state temperature of 27°C within 1100 s. Similarly, calculations were performed for the cooling transient which would follow a suspension of heating ($\dot{q}_{hx} = 0$). With the greenhouse air initially at 20°C, it was found that a steady state condition with $T_{ai} = T_{ao} = 0$°C could be reached in approximately 1350 s. Such fast transients are to be expected for a greenhouse of thin wall construction with significant infiltration. In Fig. 14 the diurnal variations of T_{ai} and T_{ao} are plotted for $\dot{q}_{hx}=0$ and meteorological conditions recorded in Indianapolis, Indiana for February 23, 1974 [13], which represents a typical cold winter day. The results show the significant contributions which can be made by solar energy in heating the greenhouse air during the day and by thermal radiation emission in cooling the greenhouse at night. The extent to which T_{ai} exceeds T_{ao} during the daylight hours provides a measure of the so-called greenhouse effect.

COUPLED PERFORMANCE CALCULATIONS

Although the models for determining the performance of the evaporative pad and the heat exchange between the greenhouse and its environment (the heat load) may now be coupled, it is important to note that this coupling may be implemented in different ways, according to how one wishes to control the system operation. The control strategy selected for this study is one which attempts to maximize the exchanger heat delivery rate during periods of heat loss by the house and which strives to match the heat exchanger air outlet temperature with the desired inside air temperature during periods of house heat gain. Such a strategy is compatible with the dual objectives of maintaining a satisfactory greenhouse environment and enhancing waste heat dissipation.

The primary means chosen for implementing the above control involves adjusting the amount of outside air brought into the greenhouse. This air enters the house through louvers upstream of the heat exchanger and passes through the exchanger before entering the crop cultivation area (Fig. 3). The maximum flow rate of the outside air would occur when there is no recirculation of house air, in which case all of the air flowing through the cultivation area is made to leave the greenhouse through the exit louvers. Although they have been combined as one term in the foregoing transient analysis, the deliberate introduction of ambient air should not be confused with infiltration due to structural leaks. To avoid confusion the rate at which ambient air is introduced to the greenhouse will henceforth be designated as $\dot{m}_{bleed}$, in which case the house air recirculation rate is $\dot{m}_{recirc} = \dot{m}_a - \dot{m}_{bleed}$. It should be noted that, in addition to varying $\dot{m}_{bleed}$, greenhouse control can also be implemented by varying $\dot{m}_a$ and/or $\dot{m}_w$.

Calculations are performed on an hourly basis using the following procedures. During periods of heat loss from the greenhouse, $\dot{m}_a$ and $\dot{m}_w$ are held constant and $\dot{m}_{bleed}$ is varied, until $\dot{q}_{hx}$ is equal to the house heat load, q_{load}, plus the heat required to raise the bleed air to the specified inside air temperature. If this requirement cannot be achieved, $\dot{m}_w$ is reduced and $\dot{m}_{bleed}$ is again varied in an effort to equalize the heat rates. However, $\dot{m}_w$ is not allowed to decrease below 5 kg s^{-1} (to prevent pad dryout), and if the desired equality is still not achieved, the total air mass flow rate $\dot{m}_a$ is then reduced and the procedure is repeated. During periods of house heat gain, the iteration procedure and matching criteria are changed. Instead of attempting to maximize heat dissipation, the objective becomes one of minimizing the difference between the heat exchanger exit temperature, $T_{a,out}$, and the desired inside air temperature, T_{ai}. The air mass flowrate $\dot{m}_a$ is held constant, and $\dot{m}_{bleed}$ and $\dot{m}_w$ are varied to achieve convergence between $T_{a,out}$ and T_{ai}.

By allowing $\dot{m}_{bleed}$ to vary in order to achieve convergence, it is possible to enhance heat dissipation by the greenhouse, $\dot{q}_{hx}$, while still maintaining a suitable value of T_{ai}. However, during periods of extreme cold, it may be necessary to set $\dot{m}_{bleed} = 0$ and to vary $\dot{m}_w$ in order to satisfy the heat load requirement. Under such conditions the sole objective would be to maintain a suitable greenhouse environment.

Preliminary diurnal calculations based on the foregoing procedures have been performed for representative days from each of the four seasons (February 24, April 30, July 24 and October 24), using 1974 weather data for Indianapolis, Indiana [13]. The water inlet temperature was held at $T_{w,in} = 40°C$, and the maximum values of $\dot{m}_a$ and $\dot{m}_w$ were arbitrarily set at 160 kg s^{-1} and 90 kg s^{-1}, respectively. Results for the winter condition are shown in Figs. 15 and 16, and the performance is excellent. The desired greenhouse temperature, $T_{ai} = 20°C$, is maintained throughout the day, and a significant bleed flow rate is maintained through much of the day. The ability to operate at high values of $\dot{m}_{bleed}$ enhances waste heat dissipation, as evidenced by the fact that the exchanger heat rate is considerably in excess of the house head load. Note also that the condenser water is cooled by as much as 30°C. The reduction in the house heat load during daylight hours is due to the effect of solar heating.

System behavior for the typical summer day is shown in Figs. 17 and 18. It is evident that the evaporative pad can maintain the greenhouse air at a temperature significantly below the warm summer ambient, with the value of $T_{a,out} = T_{ai}$ being minimized by operating at reduced values of $\dot{m}_w$. Since the relative humidity was in the range $53 \leq RH \leq 80$ for the day, the results suggest that significant evaporative cooling of the ambient air may still be achieved under humid conditions. Although the temperature drop of the water is also significant, the system does not provide for appreciable heat dissipation due to the low water flow rate. System behavior which is intermediate to the winter and summer extremes is shown in Figs. 19 through 22.

SUMMARY

The primary objective of this study has been to develop comprehensive models for evaluating the performance and optimizing the design of greenhouse complexes which use waste heat for environment control. Calculations based on these models have led to the following conclusions.

(1) By virtue of its higher heat dissipation rate, lower operating power and acquisition costs, and its potential for summer cooling, the evaporative pad heat exchanger is superior to extended-fin heat exchangers for greenhouse environment control.

(2) It is feasible to consider use of the evaporative pad to achieve significant ambient air cooling in humid regions.

(3) The feasibility of using the amount of ambient air introduced to the system as a primary control variable for maintaining suitable greenhouse temperatures and enhancing waste heat dissipation has been demonstrated. During winter conditions it appears that large amounts of heat may be dissipated, while still maintaining satisfactory greenhouse air temperatures. The calculations further suggest that little care need be exercised to reduce greenhouse heat loss, thereby allowing construction costs to be minimized.

Although a detailed model has been developed for assessing the influence of climatic, design and operating variables on waste heat utilization in a greenhouse complex, more extensive calculations are needed to evaluate and optimize system performance. The effect of more extreme climatic conditions should be considered, along with the effect of variations in powerplant operation. Calculations should also be performed to determine the effect of design changes on system performance. Consideration should also be given to developing more sophisticated interfacing and control models for the heat exchanger and greenhouse systems. Finally, efforts should be made to compare predictions based on the model with observations of actual greenhouse behavior.

NOMENCLATURE

A	area, m^2
A_{fr}	heat exchanger frontal area, m^2
c_p	specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$
d_f	fiber diameter, m

f	friction factor
G	mass velocity, kg m^{-2} s^{-1}
H	greenhouse height, m
H'	gable height, m
h	convective heat transfer coefficient, W m^{-2} K^{-1}
h_{fg}	latent heat of vaporization, J kg^{-1}
i	moist air enthalpy, J kg^{-1}
j_1, j_2	Colburn factors
k_d	convective mass transfer coefficient, kg m^{-2} s^{-1}
L	total greenhouse length, m
L'	half-width of gable base, m
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{m}_a$	heat exchanger air flow rate, kg s^{-1}
$\dot{m}_{bleed}$	ambient air flow rate into greenhouse, kg s^{-1}
$\dot{m}_{recir}$	rate of recirculation of greenhouse air, kg s^{-1}
$\dot{m}_w$	water flow rate to the heat exchanger, kg s^{-1}
n	number of gables
P_a	air circulating fan power requirement, W
p	pressure, N m^{-2}
Pr	Prandtl number
$\dot{q}$	heat transfer rate, W
r_h	hydraulic radius, m
RH	relative humidity of the inlet air
Re	Reynolds number
S	spacing between greenhouses, m
Sc	Schmidt number
T	temperature, K
t	time, s or h
V	volume, m^3
$\bar{V}$	heat exchanger air velocity, m s^{-1}
$\bar{V}_{amb}$	ambient air speed, m s^{-1}
W	greenhouse width, m
x_d, y_d, z_d	exterior dimensions of the extended fin heat exchanger, m

x_w, y_w, z_w	exterior dimensions of the evaporative pad heat exchanger, m
α	heat transfer area per unit volume, m^{-1}
β	gable tilt angle, rad
μ	viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	mass density, kg m^{-3}
ω	specific humidity, kg(water vapor)/kg(dry air)

Subscripts

a	dry air
b	greenhouse wall condition
bi	greenhouse wall inner surface condition
bo	greenhouse wall outer surface condition
ci	inside (greenhouse) convection
co	outside (greenhouse) convection
dry	dry heat exchanger
e	element of the evaporative pad
ht	heat transfer
hx	heat exchanger
i	inside (house) air condition
in	heat exchanger inlet condition
inf	air infiltration
ℓ	latent heat transfer effect
load	greenhouse heat requirement
m	mean
o	outside (ambient) air condition
out	heat exchanger outlet condition
$\mathcal{s}$	sensible heat transfer effect
s	saturated vapor conditions
sol	solar radiation
sol,b	solar radiation absorbed by a greenhouse wall
t	total
tr	thermal radiation exchange between the outside wall and the surroundings

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w	water
wet	wet heat exchanger
1,2,...,6	the six greenhouse surfaces, Fig. 11

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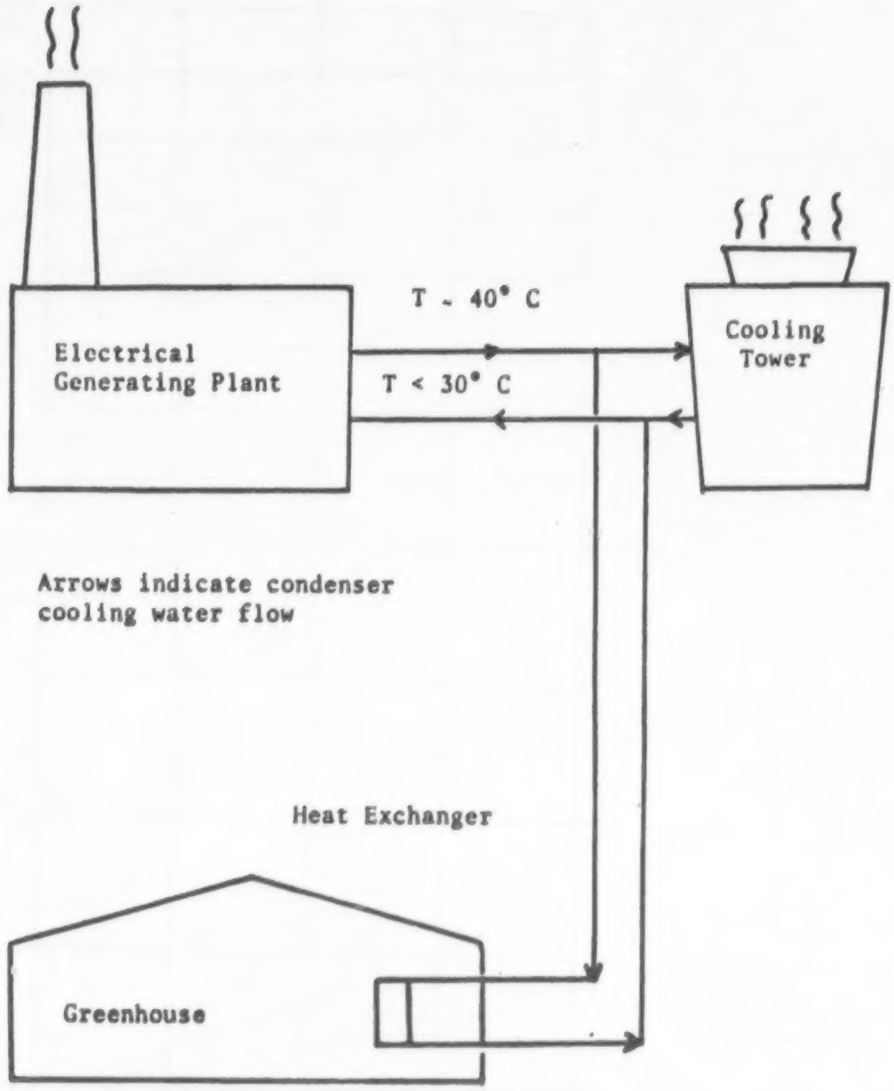

T ~ 40° C
T < 30° C
Electrical Generating Plant
Cooling Tower
Arrows indicate condenser cooling water flow
Heat Exchanger
Greenhouse

Figure 1 Waste Heat Utilization for Greenhouse Climate Control.

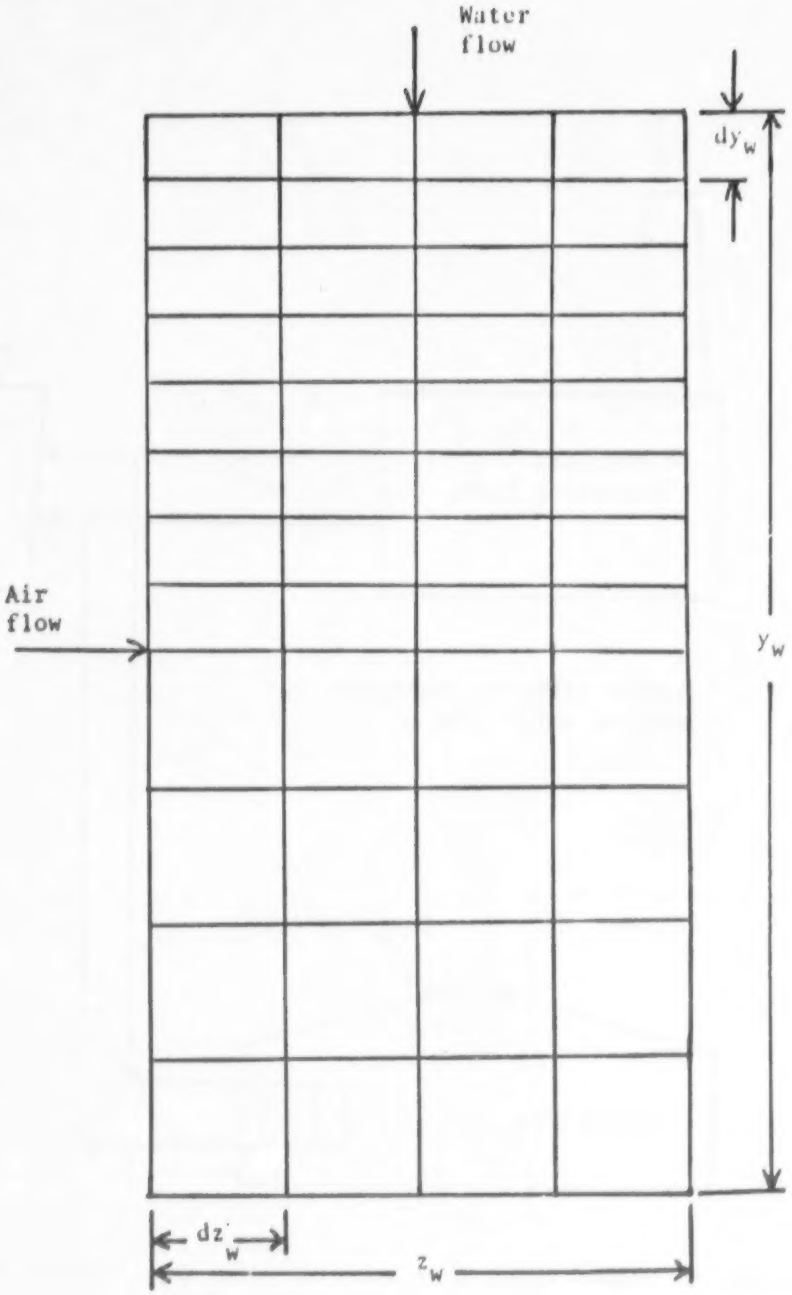

Water flow
dy_w
Air flow
y_w
dz_w
z_w

Figure 2 Network Representation of the Evaporative Heat Exchanger.

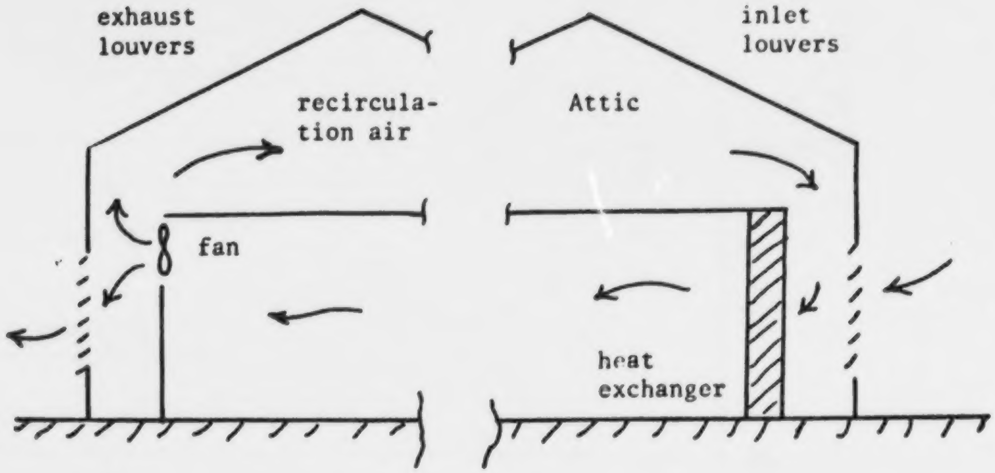

exhaust
louvers
recircula-
tion air
Attic
inlet
louvers
fan
heat
exchanger

Figure 3 Greenhouse Air Handling System.

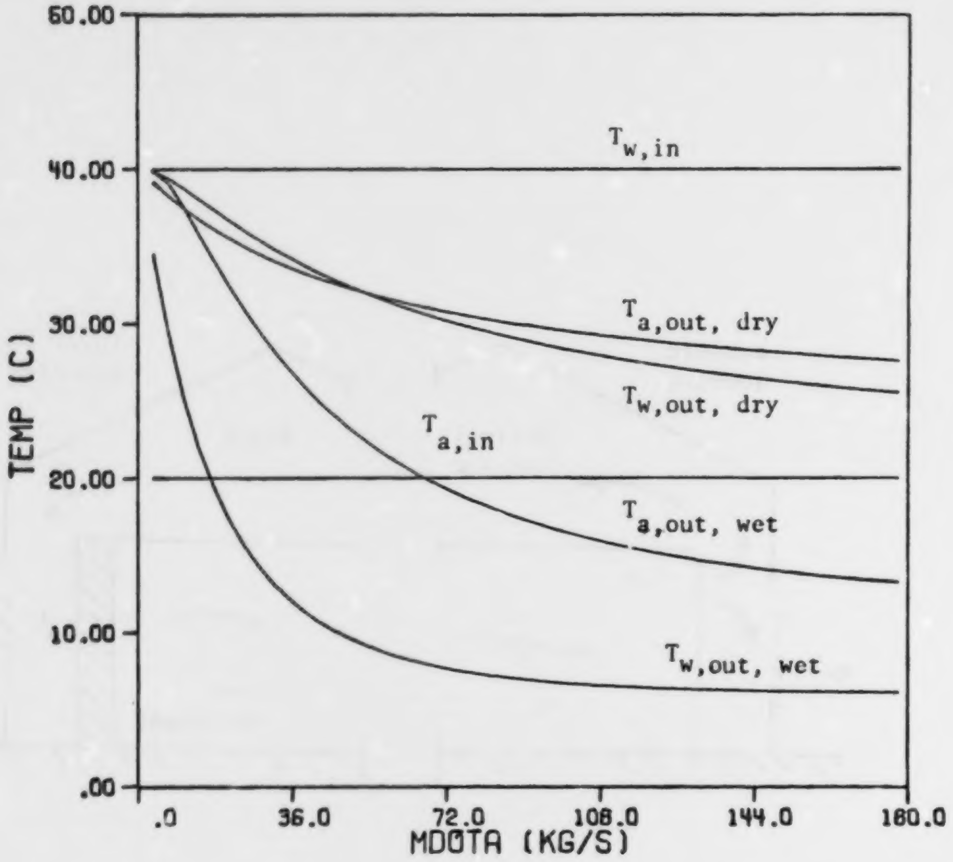


Figure 4 Fluid Outlet Temperatures as a Function of Air Mass Flow Rate ($T_{a,in}$ = 20°C, $T_{w,in}$ = 40°C, $\dot{m}_w$ = 30 kg s^{-1}, RH = 0, $A_{fr,wet}$ = 300 m^2, $A_{fr,dry}$ = 2 m^2).

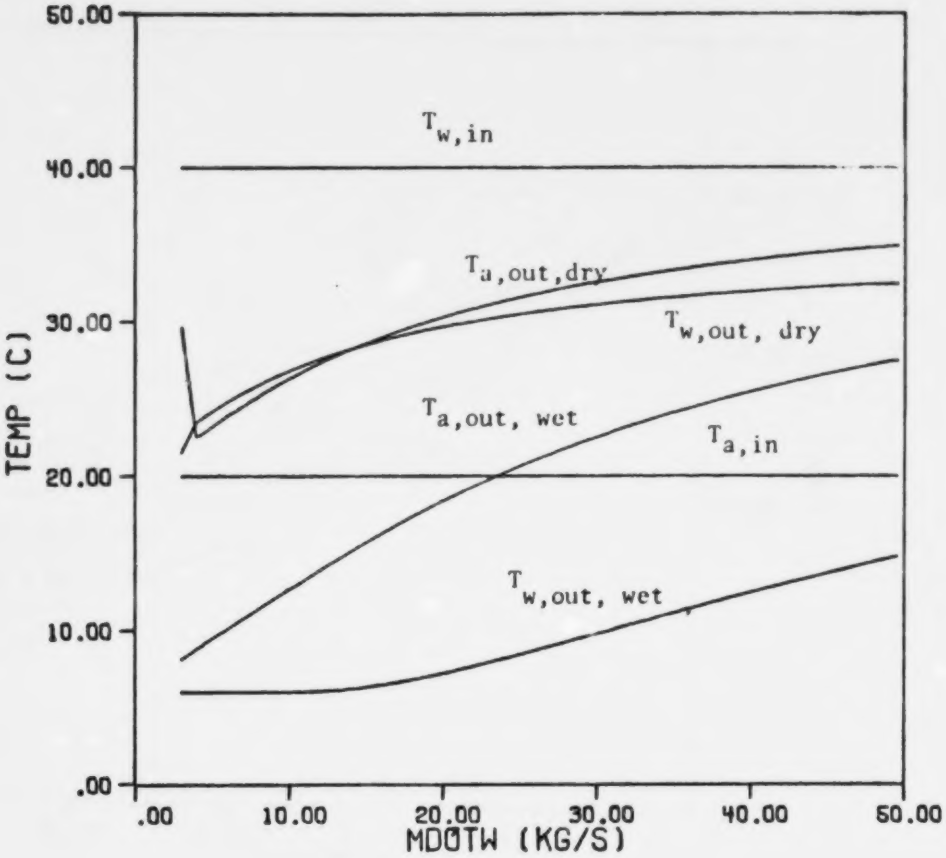


Figure 5 Fluid Outlet Temperatures as a Function of Water Mass Flow Rate ($T_{a,in}$ = 20°C, $T_{w,in}$ = 40°C, $\dot{m}_a$ = 180 kg s^{-1}, RH = 0, $A_{fr,wet}$ = 300 m^2, $A_{fr,dry}$ = 2 m^2).

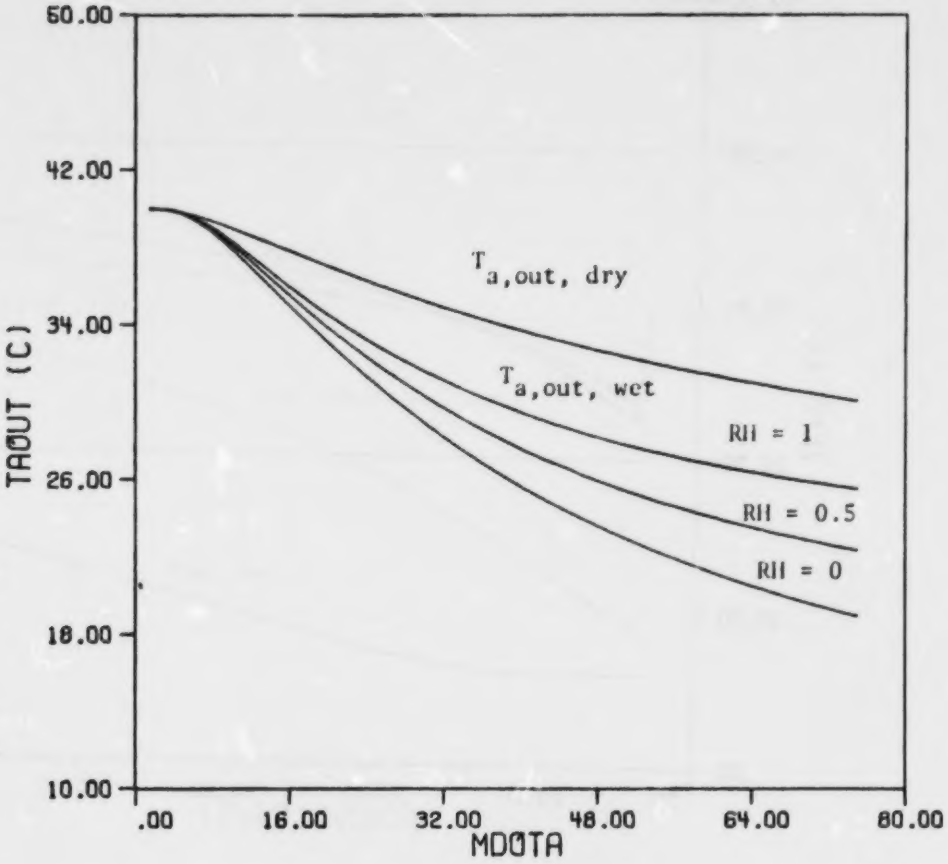


Figure 6 Effect of Air Mass Flow and Relative Humidity on the Air Outlet Temperature ($T_{a,in}$=20°C, $T_{w,in}$=40°C, $\dot{m}_w$=30 kg s^{-1}).

97<

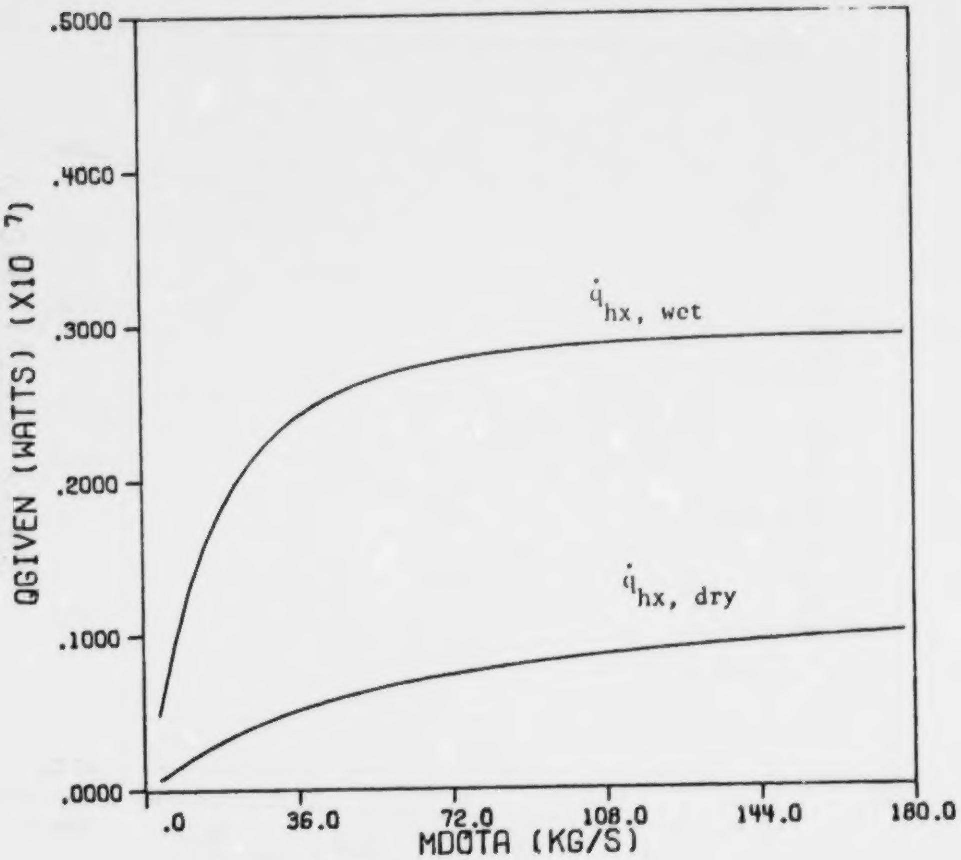


Figure 7 Heat Transfer Rate as a Function of Air Mass Flow Rate ($T_{a,in}$=20°C, $T_{w,in}$=40°C, $\dot{m}_w$=30 kg s^{-1}, RH=0, $A_{fr,wet}$=300 m^2, $A_{fr,dry}$=2 m^2).

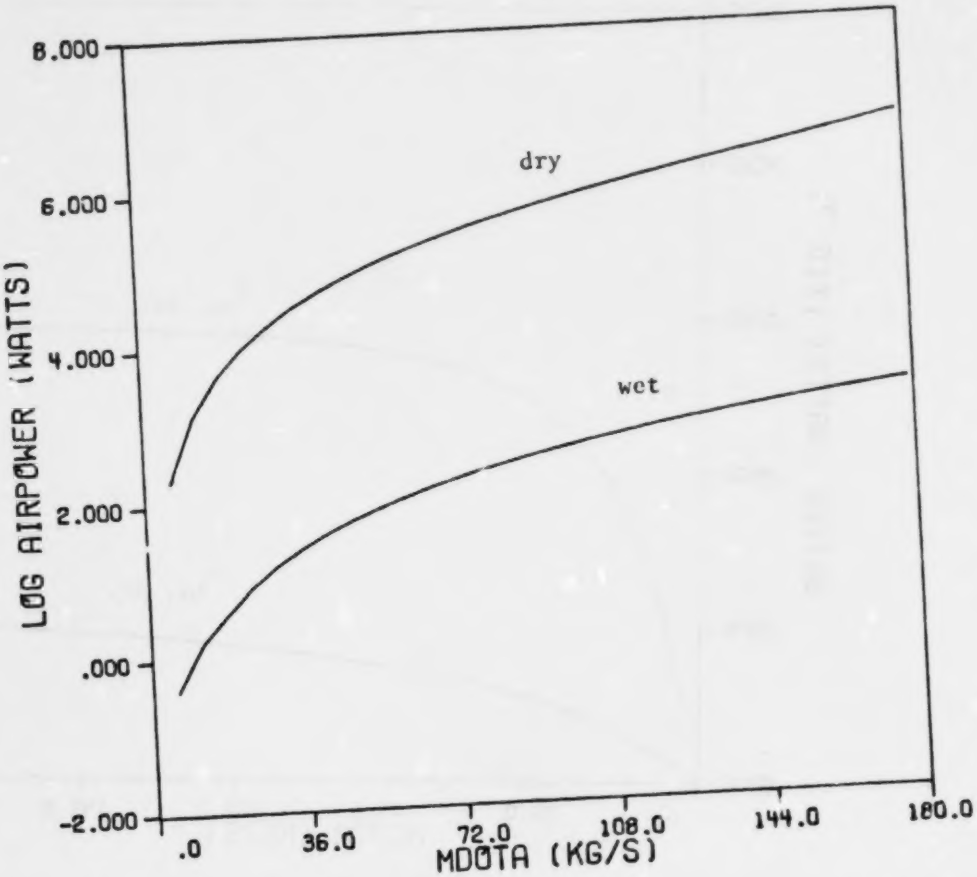


Figure 8 Fan Air Power Requirement as a Function of Air Mass Flow Rate ($T_{a,in}$=20°C, $T_{a,out}$=30°C, $P_{a,in}=10^5$ N m^{-2}, $A_{fr,wet}$=300 m^2, $A_{fr,dry}$=2 m^2).

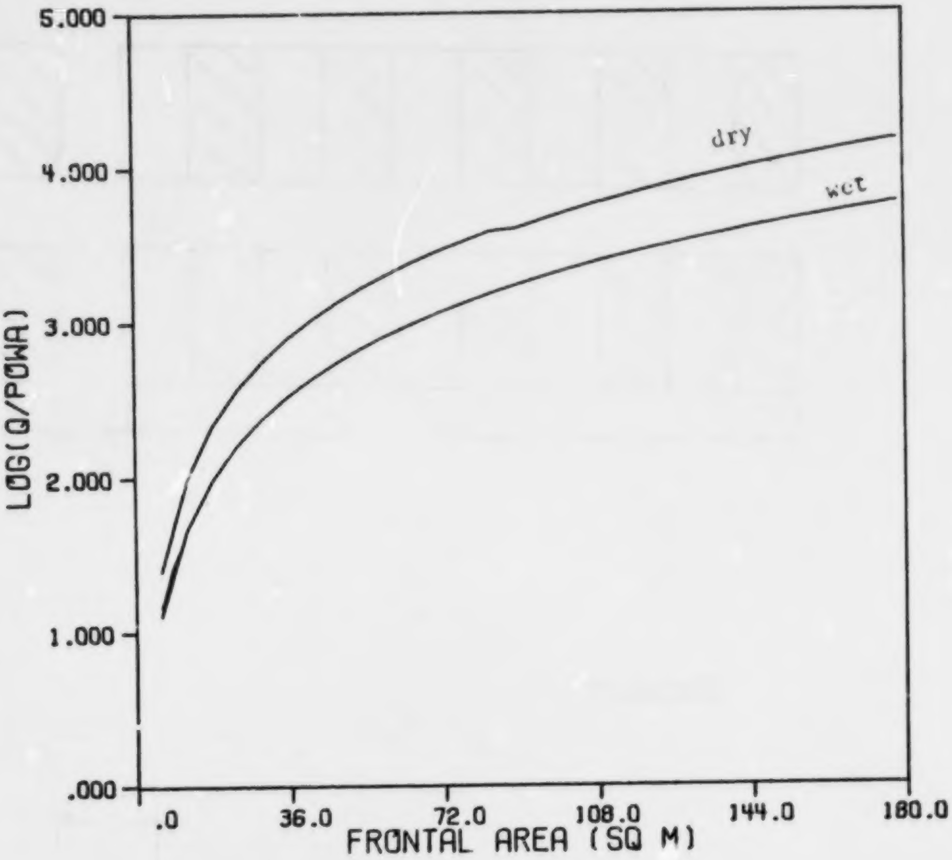
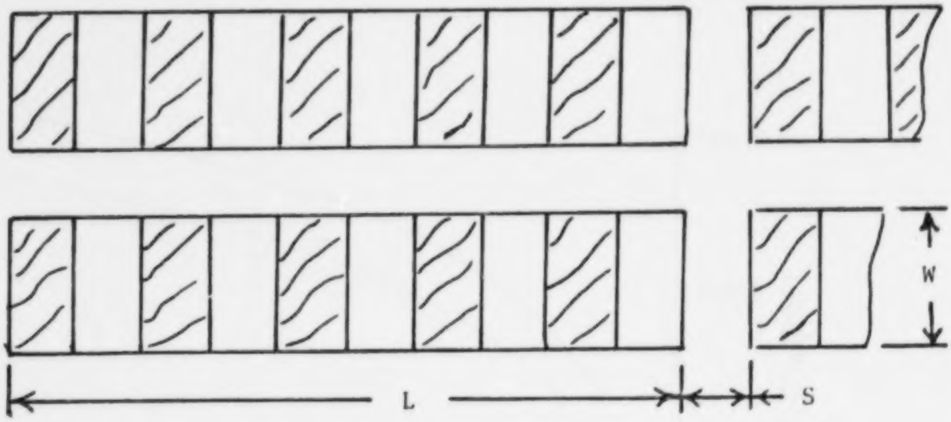


Figure 9 Effect of Frontal Area on the Heat Exchanger Power Ratio ($T_{a,in}$=20°C, $T_{w,in}$=40°C, $\dot{m}_a$=180 kg s^{-1}, $\dot{m}_w$=30 kg s^{-1}, RH=0).

Plan



Elevation

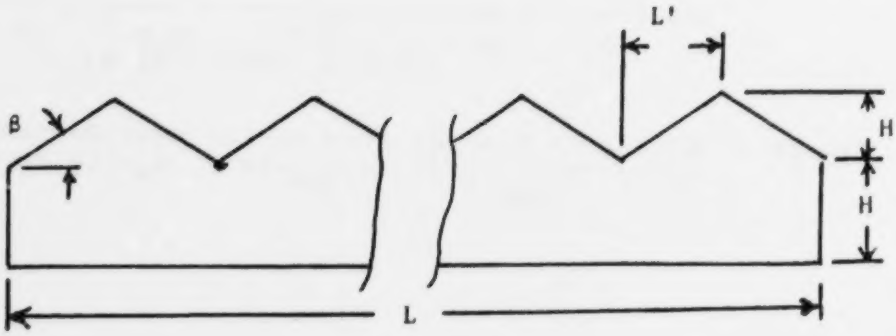


Figure 10 Plan and Elevation View of the Greenhouse System.

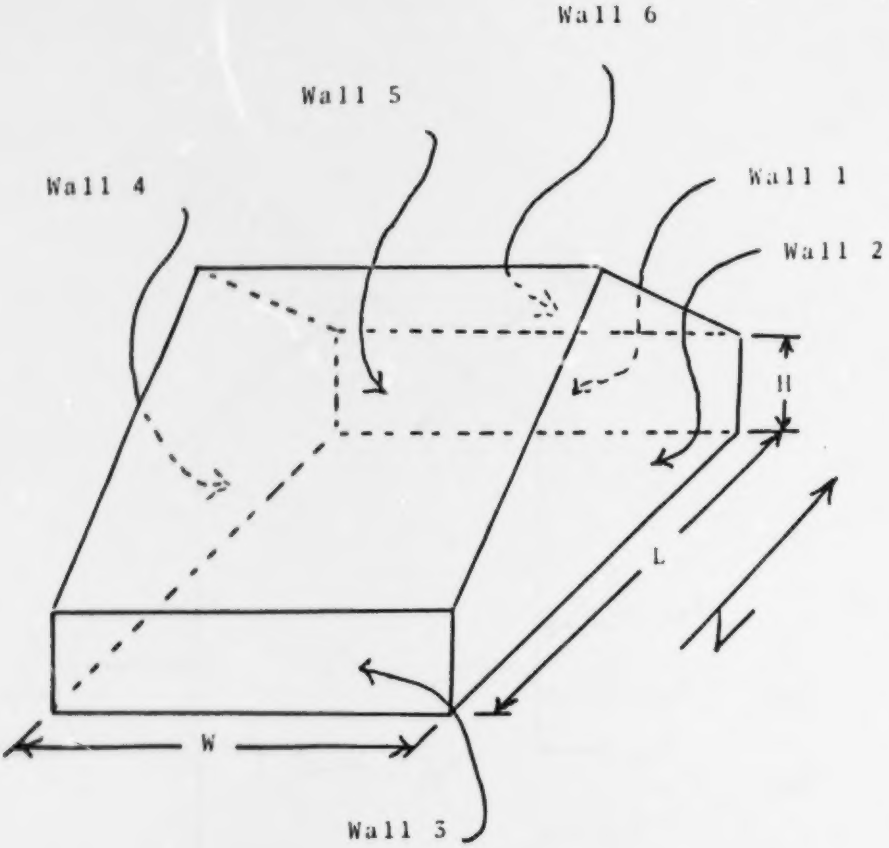

Wall 6
Wall 5
Wall 4
Wall 1
Wall 2
H
L
W
Wall 3

Figure 11 Six Wall Greenhouse Model [$A_1=A_3=WH$, $A_2=A_4=LH+n(L'H')$, $A_5=A_6=LW/2\cos\beta$].

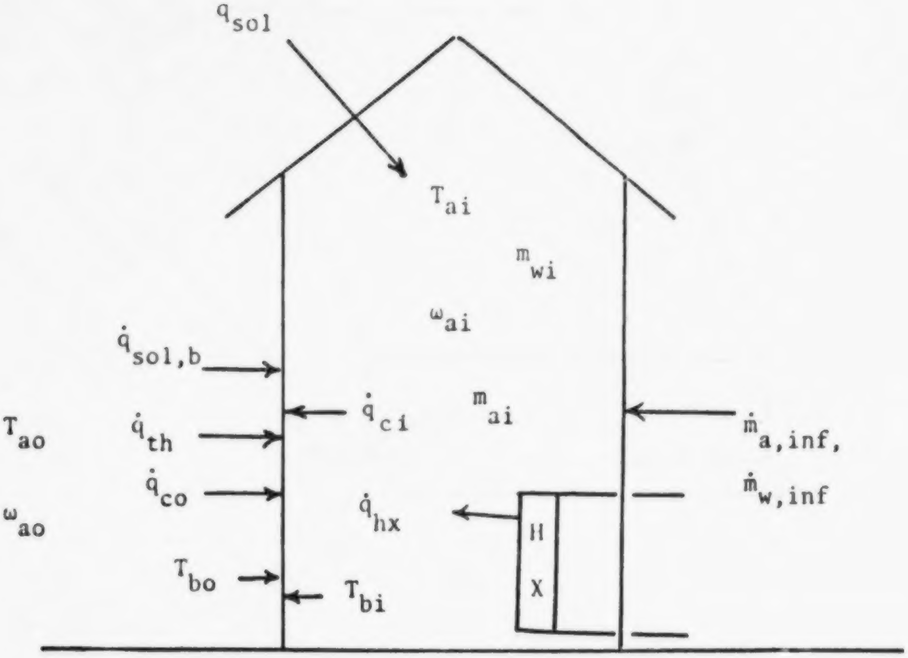

q_{sol}
T_{ai}
m_{wi}
ω_{ai}
$\dot{q}_{sol,b}$
$\dot{q}_{ci}$
m_{ai}
T_{ao}
$\dot{q}_{th}$
$\dot{q}_{co}$
ω_{ao}
$\dot{q}_{hx}$
H
X
T_{bo}
T_{bi}
$\dot{m}_{a,inf}$,
$\dot{m}_{w,inf}$

Figure 12 Greenhouse Energy Exchange Mechanisms.

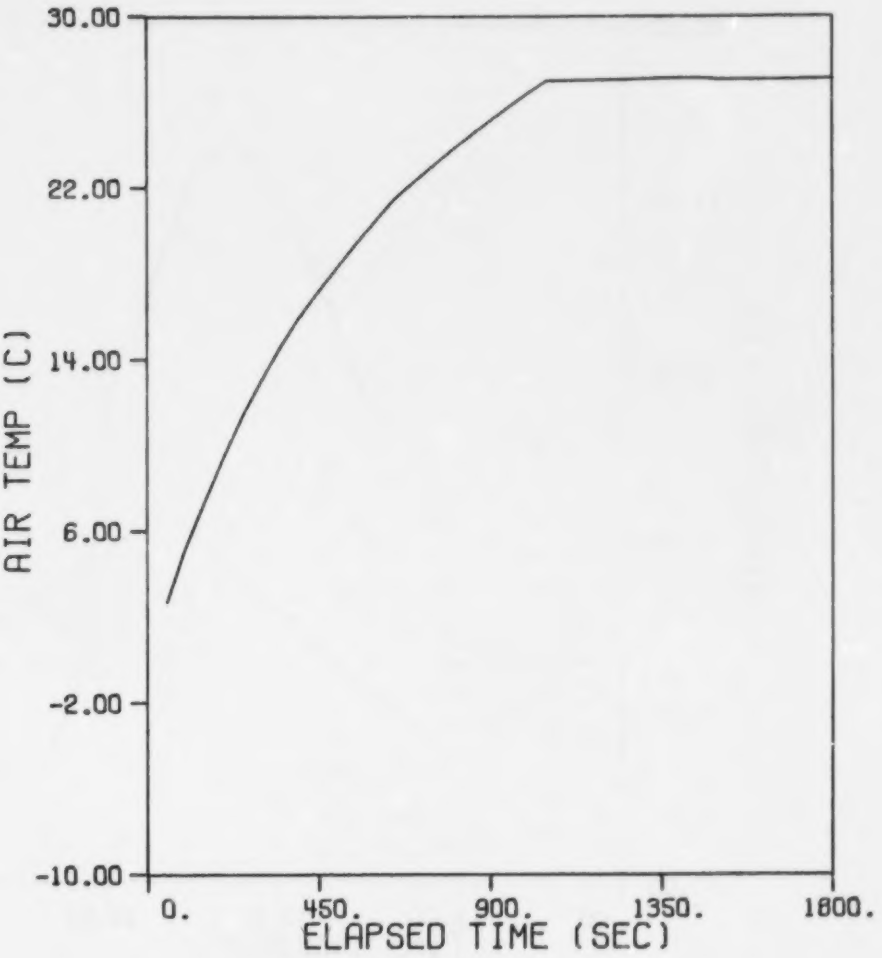


Figure 13 Greenhouse Temperature Response During a Heating Transient ($T_{ai,o}=T_{ao}=0°C$, $\dot{q}_{hx}=2MW$, $\dot{q}_{sol}=0$, $\bar{V}_{amb}=0$).

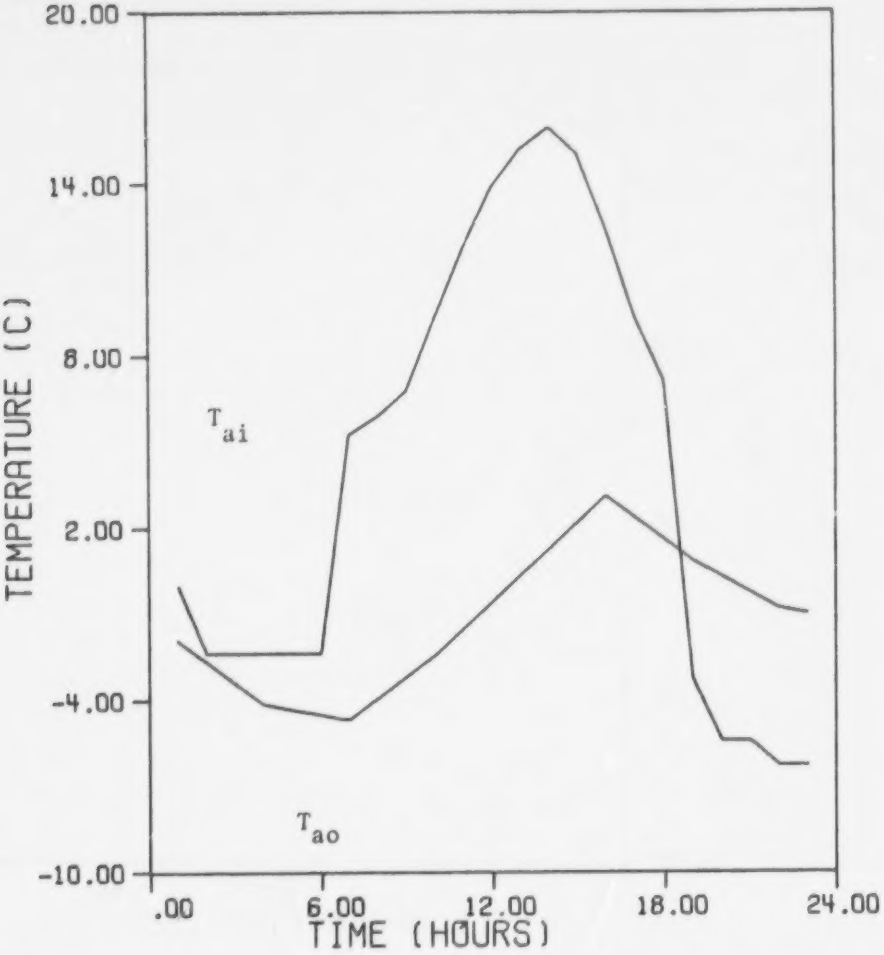


Figure 14 Diurnal Greenhouse Temperature Response with No Heating (Julian Date = 054, Indianapolis, Indiana, 1974).

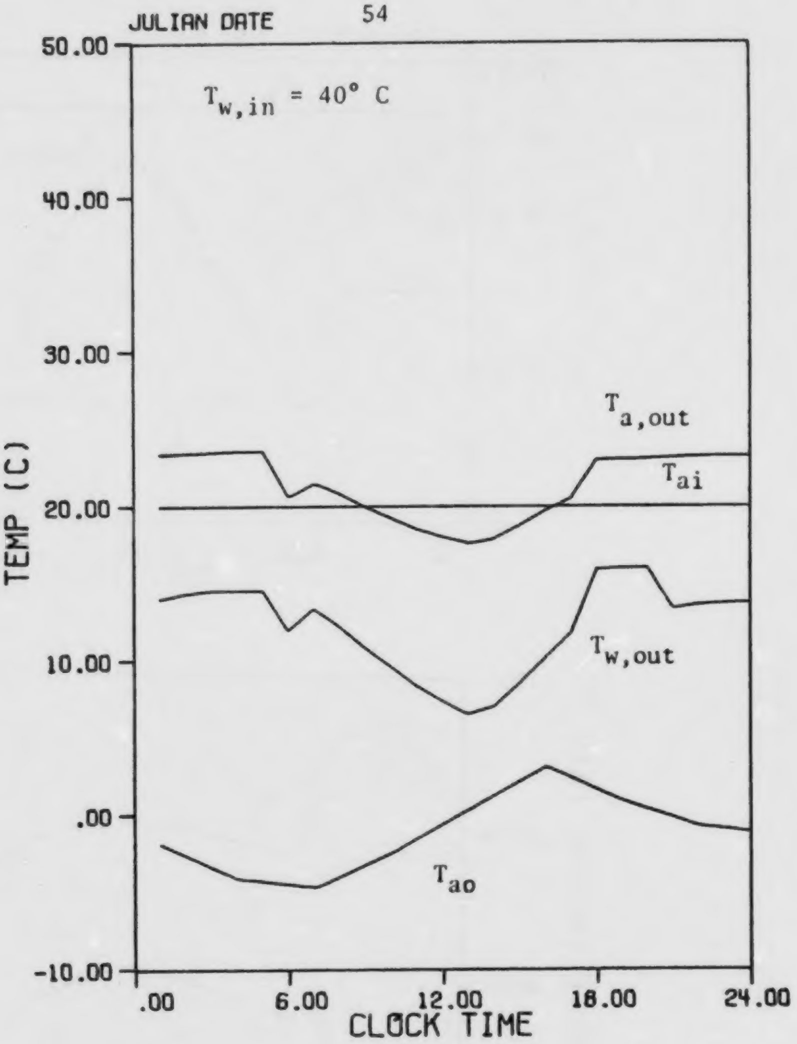


Figure 15 Winter Diurnal Temperatures.

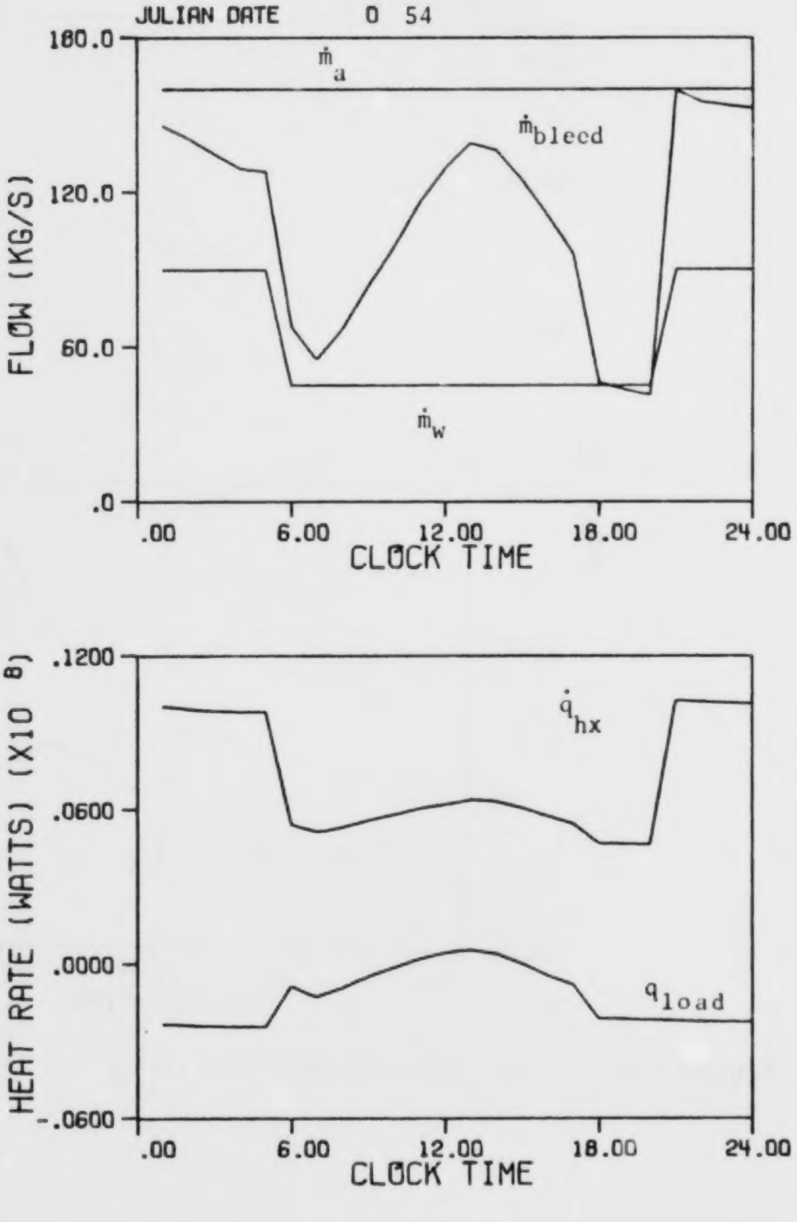


Figure 16 Winter Diurnal Flow and Heat Rates.

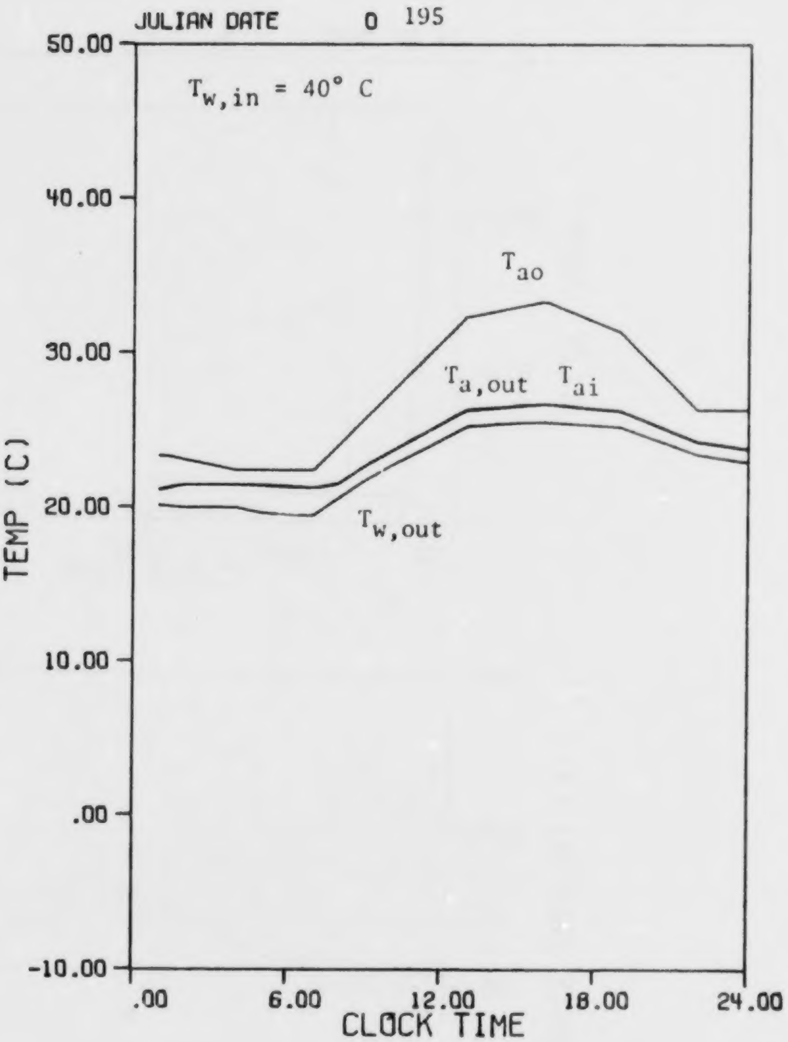


Figure 17 Summer Diurnal Temperatures.

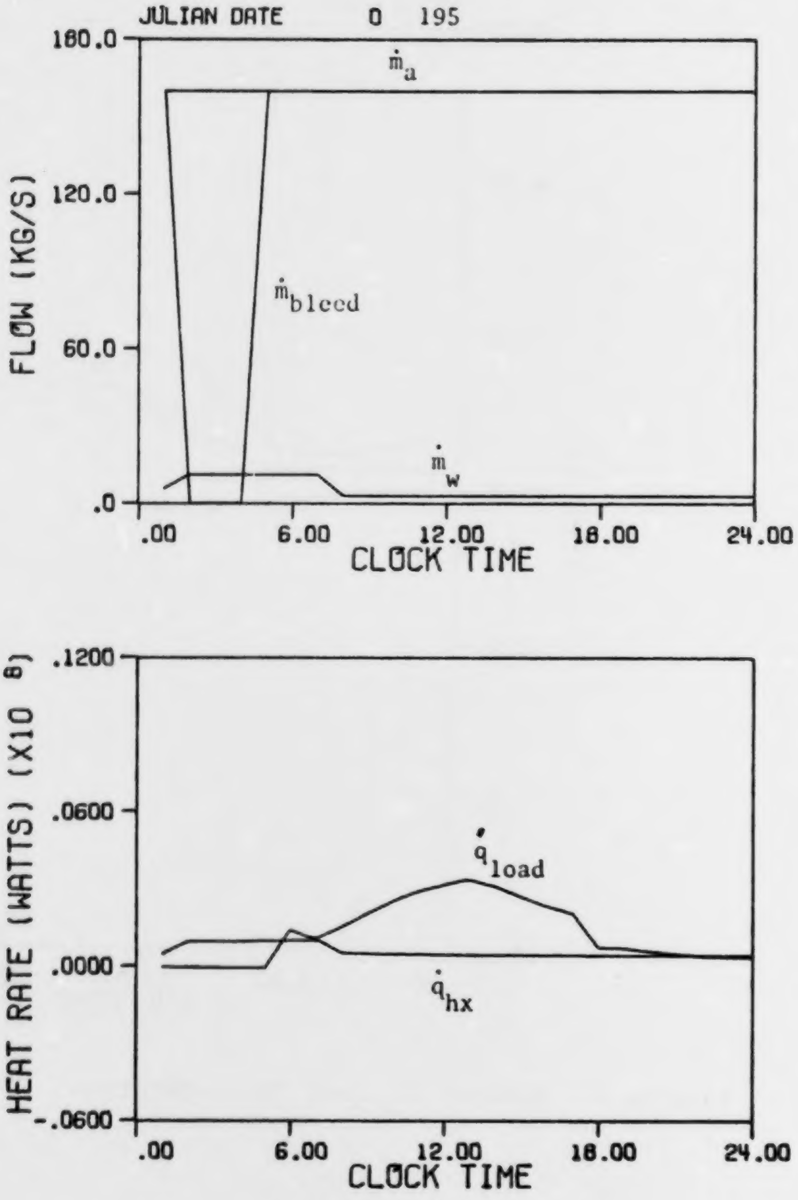


Figure 18 Summer Diurnal Flow and Heat Rates.

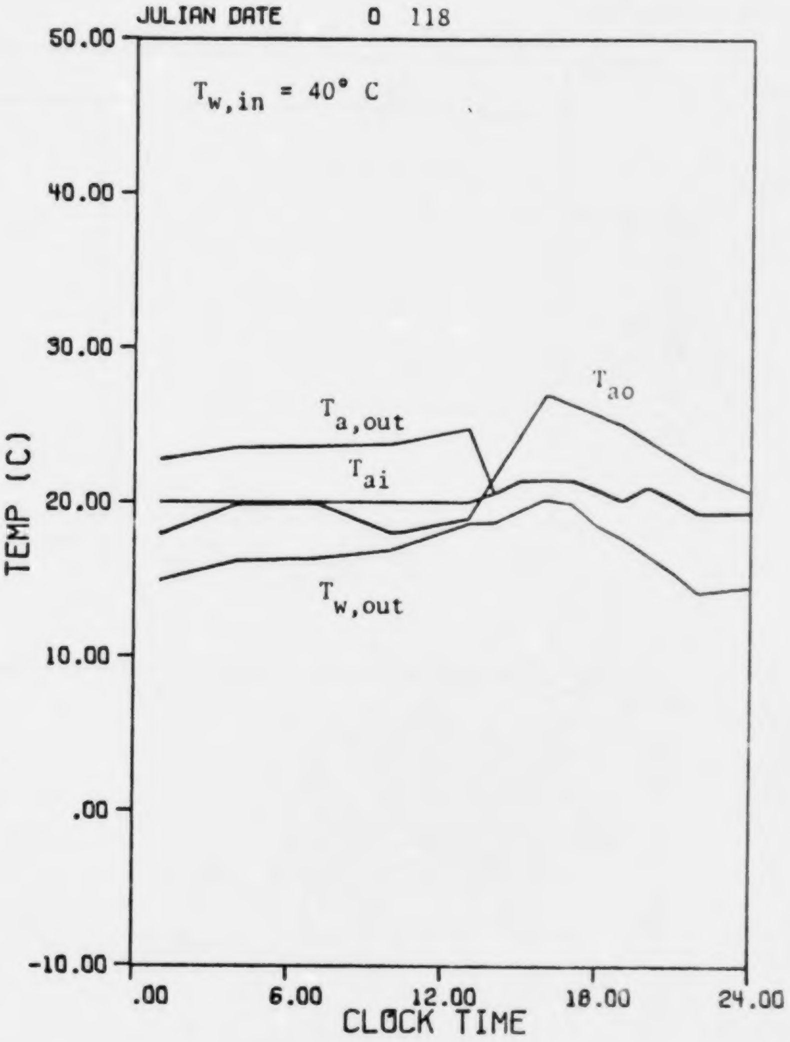


Figure 19 Spring Diurnal Temperatures.

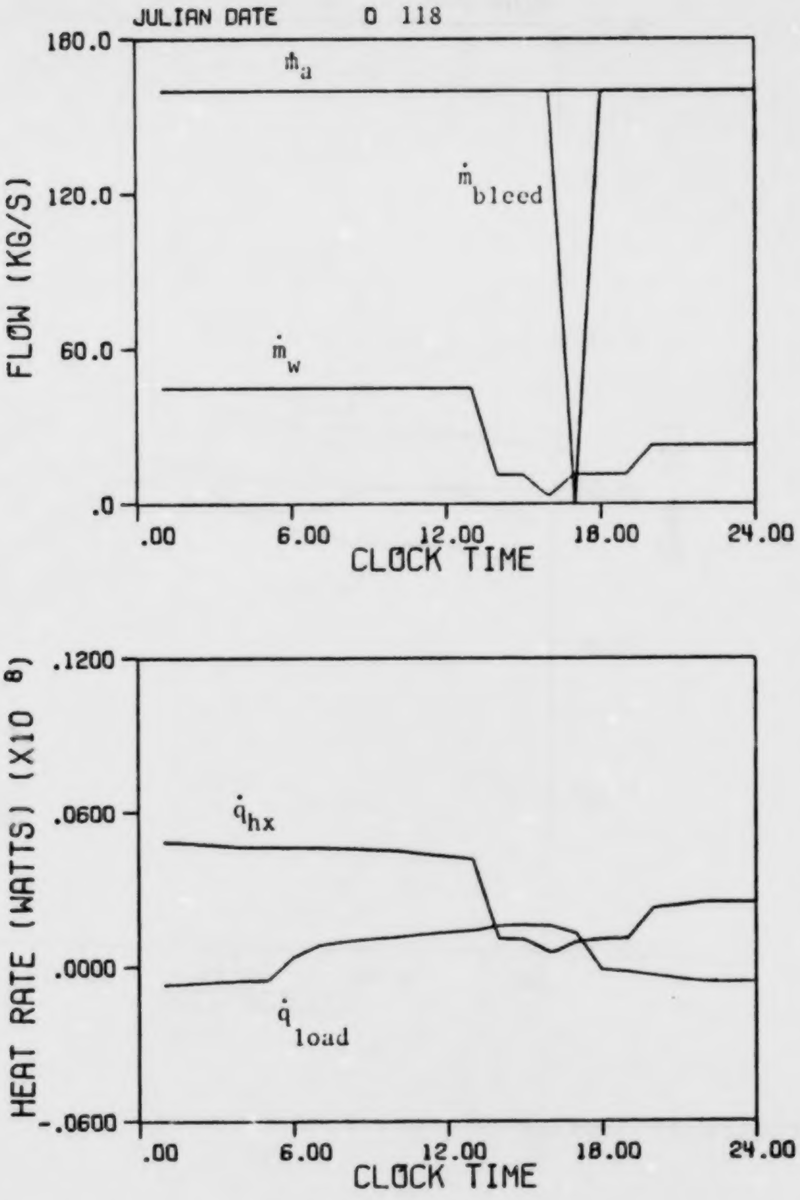


Figure 20 Spring Diurnal Flow and Heat Rates.

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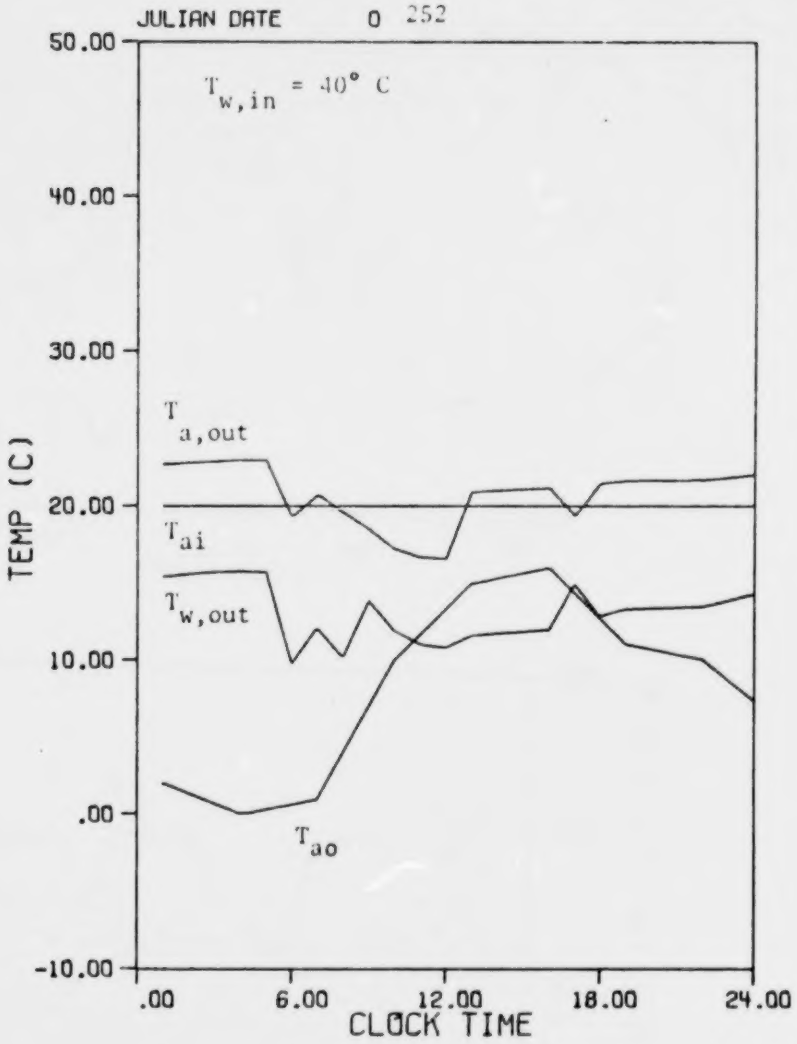

Figure 21 Autumn Diurnal Temperatures.

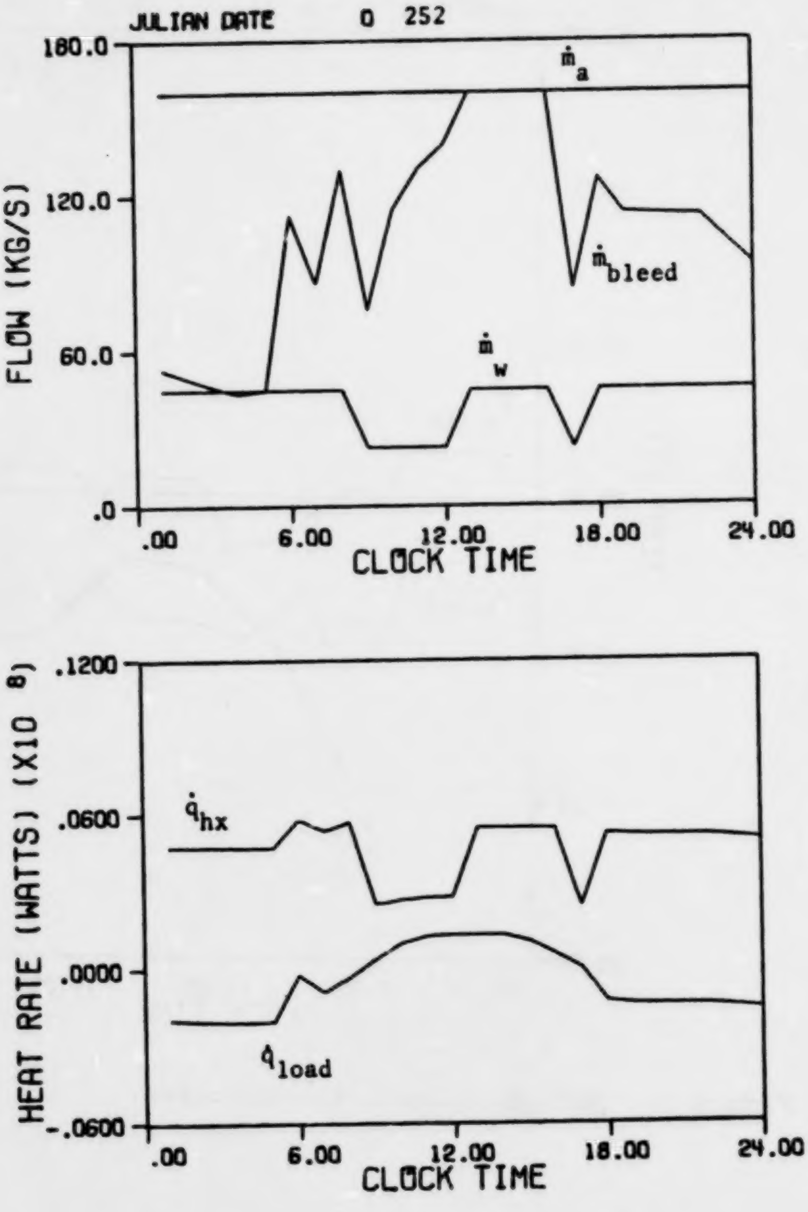

Figure 22 Autumn Diurnal Flow and Heat Rates.

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THERMAL CONTROL OF A SHALLOW POND WITH WASTE HEAT FROM A CLOSED CYCLE COOLING SYSTEM

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Purdue University
W. Lafayette, Indiana U.S.A.

ABSTRACT

The thermal response and control of a shallow pond which utilizes waste heat in a closed cycle cooling system are considered. The heat is dissipated by means of an indirect contact heat exchanger, which takes the form of a pipe network submerged in the pond. Calculations based on representative models are used to establish a heat exchanger design which provides a suitable compromise between operating costs and thermal performance. The calculations also reveal the extent to which the thermal condition of the pond may be controlled and the extent to which the design load of the primary cooling system may be reduced.

INTRODUCTION

In recent years there has been considerable interest in using shallow water bodies to effect beneficial biological conversion processes [1-9]. Such processes could involve the use of basins for the mass culture of single-cell protein [1,2], raceways for the intensive culture of animal protein [1,3,9] or the use of lagoons for biological wastewater treatment [4,7]. It is known that the rate at which the processes occur is strongly temperature dependent, and it is often recommended that waste heat from electric power plants be used to maintain optimum water temperatures, which may range from approximately 295 to 310 K (72 to 98°F). The concept of a grouped utility has been advocated, involving combined wastewater treatment-electric power plants in which waste heat is used to improve the efficiency of wastewater treatment [3].

The performance of a waste heat utilization scheme depends on both the condenser discharge temperature and the means used to dissipate heat within the system. The condenser discharge temperature will depend on several variables, which

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include cooling water flow rate, plant load, climatic conditions, and the nature of the powerplant cooling system. In this study it is assumed that the use of once-through cooling or cooling ponds is precluded by environmental restrictions and high land costs, respectively. Accordingly, a closed-cycle cooling system is assumed, in which heat is dissipated by a wet cooling tower. The use of such a cooling system in the midwest will provide a condenser discharge temperature which is typically in the range from 300 to 320 K (80 to 116°F).

The waste heat utilization pond may be operated in an open or closed flow mode [1]. Although an open system provides for greater heat dissipation, it also contributes to an undesirable loading of the condenser cooling water with organic matter [7]. Extensive filtration and chemical conditioning are then needed before the water is returned to the powerplant. In contrast, although a closed flow system is characterized by reduced heat dissipation and a large initial investment, it eliminates the need for extensive water conditioning at both the intake and discharge sides of the condenser. For this reason its use has been recommended by Boersma [6].

In this study a completely closed mode of operation is assumed (Fig. 1). Waste heat is dissipated primarily through a wet cooling tower and secondarily through a heat exchanger consisting of a network of pipes immersed in the utilization pond(s). Since the extent to which heat may be dissipated and condenser water cooling may be effected by the pipe network is limited, the ponds do not eliminate the need for a primary cooling system. However, they can contribute to reducing the design load of this system.

The objectives of this study include developing a thermal model for the heat utilization system and using the model for design and performance calculations. The model has two components, one of which considers heat exchange and operating power requirements for the pipe network and another which determines heat exchange at the air-water interface. The first component is used to optimize the network design in terms of the pipe diameter, length and spacing. It is also used to determine the effect of condenser discharge temperature, T_i, and water flowrate on both the rate of heat dissipation and the temperature, T_o, of the water leaving the network. The two components are then combined to determine the pond temperature and the performance of the heat exchanger as a function of changing climatic conditions. Calculations are performed for a hypothetical pond located in Indianapolis, Indiana, using actual climatic data for the year 1974.

Collectively, the above considerations make it possible to determine whether optimum pond temperatures can be maintained throughout the year and the extent to which temperature control can be effected by changing the inlet temperature and flow rate of the condenser water diverted to the network. They also reveal the extent to which the waste heat utilization system can reduce the load on the primary cooling system.

PIPE NETWORK DESIGN AND PERFORMANCE

Design of the waste heat utilization system necessitates specification of the diameter, length and spacing of the submerged pipes. Boersma et al. [1] considered a 40m × 40m × 0.15m algal pond and determined that heat dissipation rates of 920 W m^{-2} and 1314 W m^{-2}, respectively, would be needed to insure operation of the pond at temperatures of 23.9°C and 29.4°C during winter extremes in Portland, Oregon. They further determined that these conditions could be sustained with a network of 1 in. diameter steel pipes at 12 in. centers.

A similar system is considered in this study (Fig. 2). However, to provide for a more uniform dissipation of heat at the pond bottom, two networks are presumed to be used. The intake and discharge headers for the networks are placed at opposite ends of the pond, thus providing for a single-pass, cross-flow arrangement. The networks are assumed to be submerged in a pond of uniform temperature T_p. This assumption is reasonable by virtue of the turbulent mixing which will exist in the pond due to buoyancy, wind-shear and/or mechanical action.

Calculations to determine optimum combinations of L, D and S are based on a model which considers conditions for a unit surface area of the pond. They are also based on meeting a representative winter heat load and not, for example, on achieving a prescribed temperature reduction, T_i-T_o, for the condenser water flowing through the network. The specific value of the heat load selected for the design calculations is $q_d'' = 1000$ W m^{-2}. From procedures described in the following section, this value has been found to be representative of the average heat loss which would have occurred for a pond maintained at 303 K (86°F) in Indianapolis, Indiana during the winter of 1974. The objective is then to obtain a design which satisfies these requirements ($q''_d = 1000$ W m^{-2}, $T_p = 303$ K) without incurring excessive initial and operating costs.

The pipe spacing S may be expressed as

$$S = (N'' L)^{-1} \tag{1}$$

where N", the number of pipes per unit pond surface area required to achieve the desired dissipation, is

$$N'' = (q''_d/q_L) \tag{2}$$

If the values of q_L and L may be found by other means, S may then be determined for the prescribed heat dissipation.

The heat transfer from a pipe of length L may be obtained by integrating the following expression from x=0 to x=L

$$dq = \frac{[T(x) - T_p]dx}{R_t} \tag{3}$$

The expression applies to a differential element of length dx, and the thermal resistance to heat transfer between the condenser water in the pipe and the pond water may be expressed as

$$R_t = R_i + R_c + R_o$$

$$= \frac{1}{h_i \pi D_i} + \frac{\ell n(D_c/D_o)}{2\pi k_c} + \frac{1}{h_o \pi D_c} \tag{4}$$

Although the resistance to conduction through the pipe wall has been neglected, the conduction resistance associated with any coating which forms on the outer surface may be significant and has been included. Assuming fully developed flow the inside convection coefficient is obtained from [10]

$$h_i = 3.66 \frac{k_w}{D_i} \qquad (Re_D < 2300) \tag{5}$$

$$\text{or} \quad h_i = (0.027\, Re_{D_i}^{0.8}\, Pr_w) \frac{k_w}{D_i} \qquad (Re_D \geq 2300) \tag{6}$$

Assuming that heat transfer from the outer surface is exclusively by free convection, the outside convection coefficient may be expressed as

$$h_o = C(\text{Gr Pr}_w)^m \frac{k_w}{D_c} \tag{7}$$

where the values of C and m depend upon the (Gr Pr_w) product [10]. Since conditions in the water outside the pipewall are likely to be characterized by significant mixing, equation (7) should be viewed as providing a lower (conservative) estimate of h_o.

Equation (3) must be solved in conjunction with a simple energy balance for water flowing through the element dx. That is,

$$dq = \dot{m}c_p dT \tag{8}$$

where the water mass flowrate in the pipe is

$$\dot{m} = \rho V(\pi D_i^2/4) \tag{9}$$

Beginning with the condition that $T(0)=T_i$, an iterative, step-by-step marching solution may be effected in which T is determined as a function of the distance x along the pipe. Taking the solution to x=L, the outlet temperature T_o and the pipe heat transfer q_L may then be determined. The result is of the form

$$q_L = \int_o^L \frac{T(x)-T_p}{R_t} dx = \dot{m}c_p(T_i-T_o) \tag{10}$$

Note that the flowrate $\dot{m}$ is an important independent variable for the system, and on a unit area basis it may be expressed as

$$\dot{m}'' = \dot{m}N'' = \frac{\dot{m}}{SL} \tag{11}$$

A rational design of the pipe network necessitates estimating the operating and initial costs of the system. Operating costs are determined by the power required to pump water through the network, and on a unit area basis this power may be expressed as

$$P'' = N''P_L = N'' \frac{\dot{m}}{\rho} \Delta p \tag{12}$$

where P_L is the power required to maintain flow through a single pipe and Δp is the pipe pressure drop

$$\Delta p = f \rho \frac{L}{D_i} \frac{V^2}{2} \tag{13}$$

The friction factor f is known as a function of Reynolds number and surface roughness [11]. Combining equations (9), (12) and (13) the power requirement may then be expressed as

$$P'' = N'' \frac{\pi}{8} f \rho D_i L V^3 \tag{14}$$

A measure of the pumping power requirement of the network relative to its ability to dissipate heat may also be obtained by defining an effectiveness of the form

$$\varepsilon = \frac{q''_d}{P''} \tag{15}$$

and an efficient network design is one which maximizes this quantity. While equation (14) provides the basis of determining operating costs, initial costs may be determined from an expression of the form

$$C'' = N'' L C' \equiv L''C' \tag{16}$$

where C' is the installation cost per unit length of pipe, C" is the cost per unit pond area and L" is the total pipe length required per unit area.

Although calculations may now be performed to obtain a suitable network design, it is useful to first consider the various contributions to the resistance to heat transfer through the pipe, equation (4). A strong tendency towards coating or scaling of the outside pipe surface would exist for each of the possible pond applications. In a waste water treatment system this coating could take the form of a layer of sludge. Calculations have been performed to determine the effect of such a layer on heat exchanger performance [12], and the effect has been found to be critical. For example, the pipe length L required to cool the condenser water from $T_i = 313$ K to $T_o = 306$ K with $T_p = 303$ K varies from approximately 50 m for a clean surface to more than 200 m for a surface with a 3 mm coating. Such a result demonstrates the importance of maintaining a clean outer surface, without which the concept of using an indirect contact heat exchanger becomes impractical. In subsequent calculations a clean surface for which $D_c = D_o$ is therefore assumed.

The effect of the flowrate $\dot{m}''$ on the inner resistance R_i is shown in Fig. 3. The calculations were performed for a representative system involving Schedule 40, 1 inch pipe with L = 30 m and $S/D_o = 4.5$. Although R_i decreases with increasing $\dot{m}''$, it is obvious that a point of diminishing return is reached. When R_o exceeds R_i by a factor of 3 or more, there is little advantage to further increasing $\dot{m}''$, particularly in view of the fact that any such increase must come at the expense of increased operating costs. At this point flowrate adjustments become ineffective from the standpoint of maintaining thermal control. However, a significant increase in heat dissipation could still be obtained by reducing R_o. The effect of such a reduction is shown in Fig. 4, where q_d'' and T_o are plotted as a function of the fraction of the outside resistance based on equation (7). A reduction in R_o by 50%, which could be promoted by mechanical mixing in the pond water, would, for example, increase q_d'' by approximately 10%.

Parametric calculations based on the foregoing model have been performed to establish a suitable network design. It is required that the network be able to dissipate $q_d'' = 1000$ W m^{-2}, with the pond maintained at a uniform temperature of 303 K. Pipe inlet temperatures T_i in the range from 307 K (93.2°F) to 320 K (116.6°F) are considered, along with temperature drops, T_i-T_o, ranging from 2°C (3.6°F) to 15°C (27.0°F). Schedule 40 pipe sizes of 1 in ($D_i = 0.0266$ m, $D_o = 0.0334$ m), 3 in ($D_i = 0.0779$ m, $D_o = 0.0889$ m) and 6 in ($D_i = 0.154$ m, $D_o = 0.168$ m) were also considered, with the outer surface assumed to be clean. In addition a value of V = 0.3 m s^{-1} was used for the design calculations. This value was selected on the basis of a trade-off which exists between the effect of V on the pump power requirements P" and its effect on initial investment C". An increase in V will decrease R_i, thereby allowing for an increase in S or a reduction in L needed to achieve a prescribed value of q_d''. The net effect is to reduce C". However, P" varies as the velocity cubed, and any increase in V could significantly increase operating costs. From the results of calculations presented elsewhere [12], it was found that a reasonable compromise could be achieved with V ~ 0.3 m s^{-1}.

Fig. 5 shows the pipe length L required to achieve various values of T_o as a function of T_i for the smaller pipe size. It is evident that, for a fixed value of T_i, the pipe length increases exponentially with increasing (T_i-T_o). A significant penalty would therefore be incurred if one chose to maximize condenser water cooling by forcing the value of T_o to approach T_p. For example, a reduction in T_o from 307 to 305 K would require increasing L by approximately a factor of two, thereby doubling both initial and operating costs. This trend applies irrespective of pipe diameter, although the required length also increases with increasing diameter. For fixed V, $\dot{m}$, and therefore q_L, increases as the square of D_i, in which case the network must dissipate more heat for a prescribed $(T_i - T_o)$, necessitating longer pipes.

Fig. 5 also reveals the obvious result that, for fixed T_o, L must increase with increasing T_i. It should be noted, however, that this trend does not apply to the total pipe length, $L'' \equiv N''L$, required per unit surface area. If multiplied by the pond surface area, this quantity would provide the total length of pipe required to maintain the prescribed conditions. From Fig. 6 it is evident that, for fixed T_o, L" decreases with increasing T_i. Hence, although L increases with T_i, the reduction in N" is more than sufficient to provide an overall reduction in L". This condition is obviously desirable from the standpoint of reducing network initial and operating costs. However, it is undesirable from the standpoint of powerplant operation, where achieving maximum efficiency depends on minimizing T_i. As with any waste heat utilization scheme, the pond must accept the condenser discharge, regardless of temperature.

Representative results for the pipe spacing to diameter ratio, S/D_o, are shown in Fig. 7. These results are approximately independent of diameter over the range considered. The benefits to be derived from operation at elevated values of T_i, as well as T_o, are again evident.

The feasibility of using waste heat in ponding systems will depend critically on economic factors. Pump power requirements will contribute significantly to operating costs, and representative results are shown in Fig. 8. Once again the trade-off between optimizing the performance of the waste heat utilization system and operating the powerplant efficiently is evident. Any reduction in T_i or T_o must come at the expense of increased pumping power. The effectiveness may be obtained by dividing P" into $q_d'' = 1000$ W m^{-2}, and one finds that for each kilowatt of pumping power, ten or more megawatts of heat are dissipated.

Representative results for the initial pipe cost are shown in Figs. 9 and 10. Although L" decreases with increasing diameter, it is clear that C" is an increasing function of diameter. This trend is a consequence of the sharp increase in pipe installation costs with increasing diameter. At 1975 prices values of C' equal to 1.55, 6.92 and 20.88 $\$\ \mathrm{m}^{-1}$ are typical of Schedule 40 galvanized pipe of 1 in, 3 in and 6 in diameters, respectively [13]. The advantage of using the 1 in pipe is apparent. Note that C" decreases with increasing T_i and T_o.

The foregoing results may be used to establish a network design which provides a suitable compromise between cost and thermal efficiency. In the interest of minimizing initial costs, it is clearly desirable to use the one inch pipe. Moreover, it would not be unreasonable to require that the network provide a water temperature drop of 5°C or more during the prescribed winter conditions. From Fig. 5 it is seen that, for values of T_i which exceed T_p by 7°C or more, this condition is generally possible for L = 30 m. For this value of L and for $T_i = 313$ K, which is representative of a closed cycle cooling system, a temperature drop of 7°C would be experienced by the condenser cooling water. From Fig. 7 it is found that the value of S/D_o needed to sustain this temperature drop, as well as a heat dissipation of 1000 W m^{-2}, is approximately 4.5. A value of $S = 4.5 \times 0.0334$ m = 0.15 m is therefore recommended. From equations (1) and (16) the corresponding values of N" and L" are then 0.222 m^{-2} and 6.67 m m^{-2}, respectively.

The model of this section may also be used to evaluate the performance of the specified network ($L = 30$ m, $D_o = 0.0334$ m, $S/D_o = 4.5$). This performance is determined by the dependent variables q''_d, P" and T_o, which in turn depend upon T_i, T_p and $\dot{m}''$. The quantities T_i and $\dot{m}''$ are of special interest, since, to varying degree, they may be treated as control variables. Of course, the extent to which T_i may be varied is limited by power plant requirements, but no such limitation pertains to $\dot{m}''$.

The effect of T_i and $\dot{m}''$ on the heat dissipation, q''_d, is shown in Fig. 11 for a pond temperature of $T_p = 298$ K. The increase in q''_d with increasing $\dot{m}''$ is due to a reduction in the internal resistance R_i, as well as to an increase in the average temperature difference, $(T-T_p)_L$, along the pipe. However, the extent to which q''_d may be increased by increasing $\dot{m}''$ is limited by the fact that $(T-T_p)_L$ may not exceed (T_i-T_p) and that the contribution of R_i to R_t eventually becomes negligible. Hence, since an increase in flowrate will also increase pump power requirements, Fig. 12, an upper limit should be imposed on the value of $\dot{m}''$. According to the results of Figs. 11 and 12, a requirement

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that $\dot{m}'' \lesssim 0.04$ kg s^{-1} m^{-2} appears to be reasonable for the prescribed network configuration. If one wishes to achieve higher dissipations, measures other than increasing $\dot{m}''$ beyond 0.04 kg s^{-1} m^{-2} should be adopted. A preferred alternative would be to decrease R_o by inducing a forced circulation and/or turbulent mixing of the pond water over the pipe. Although q''_d could also be increased by increasing T_i, this is not likely to be a viable alternative. The effect of flowrate on the temperature of the water leaving the network is shown in Fig. 13, and from the standpoint of maximizing condenser water cooling, it is obviously desirable to operate at low flowrates.

Collectively, the foregoing results indicate a trade-off with regard to flowrate. It is desirable to operate at reduced flowrates to minimize operating costs and to achieve low outlet temperatures. However, if the flowrate is too low, for example $\dot{m}'' \lesssim 0.02$ kg s^{-1} m^{-2}, it may become difficult to effect the desired heat dissipation. From the results it appears that a flowrate in the range $0.02 \lesssim \dot{m}'' \lesssim 0.04$ kg s^{-1} m^{-2} would provide a suitable compromise. For the prescribed design this range corresponds to $0.090 \lesssim \dot{m} \lesssim 0.180$ kg s^{-1} and $0.161 \lesssim V \lesssim 0.323$ m s^{-1}.

POND THERMAL BEHAVIOR

Although the foregoing results provide pertinent information concerning the design and performance of the pipe network, they were obtained by arbitrarily prescribing the pond temperature T_p. However, the value of T_p depends on climatic conditions, as well as on the condition of the condenser water pumped through the network.

The model used for this portion of the study is based on the system of Fig. 14. Heat is dissipated to the pond from the pipe network, at the same time that energy transfer between the pond and its surroundings occurs across the air-water interface. Contributions to this energy transfer are due to the incident solar and atmospheric radiation, radiation emission from the surface, the convection of sensible energy, and the convection of latent energy due to evaporation. Assuming complete mixing within the pond, the appropriate energy balance is then of the form

$$(\rho c_p d) \frac{dT_p}{dt} = q''_d + q''_{s,inc} - q''_{s,ref} + q''_{a,inc}$$

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$$- q''_{a,ref} - q''_{em} - q''_{ev} - q''_{c} \qquad (17)$$

The heat dissipation may be determined from the methods of the preceding section, and the fluxes at the air-water interface may be obtained from established procedures, which are discussed elsewhere [12].

The pond thermal response to changing climatic and network inlet conditions may be obtained from equation (17). The calculations of this study involve a hypothetical pond located in Indianapolis, Indiana, with climatic conditions corresponding to those reported by the National Climatic Center for the year 1974 [14]. The calculations were performed on a monthly basis. In each case T_p was set equal to 297 K at 12 AM on the first day of each month, and the transient calculations were initiated. Depending upon the climatic and network inlet conditions, the effect of this assumption on the calculated results would become negligible some time between the second and sixth day of the month.

The seasonal variation of T_p for a pond of d = 2 m is shown in Fig. 15, where results are compared for heated and unheated ($q''_d = 0$) conditions. The plots are based upon the noontime results for the fifteenth and last day of each month, with January 15 corresponding to the origin of the abscissa. The results indicate that, for the prescribed network design and inlet conditions of $\dot{m}'' = 0.04$ kg s^{-1} m^{-2} and $T_i = 310$ K, it is possible to maintain the pond at near optimum temperatures throughout the year. In the heated state, temperatures in excess of 300 K (80°F) can be maintained throughout the year, whereas in the unheated state temperatures in excess of 295 K (71°F) will exist for only three months of the year. The results also suggest the extent to which thermal changes would occur if heating ceased, as, for example, from a powerplant shutdown. The reduction in pond temperature which would occur during the summer would only serve to slow the biological rate processes occurring within the pond. However, the reduction associated with other periods of the year would severely inhibit, if not completely terminate, these processes. For d = 2 m the time required to proceed from the heated to unheated condition following plant shutdown is approximately four days.

Limitations associated with using the system for waste heat dissipation are shown in Fig. 16. Although significant heat dissipation and condenser water cooling occur during the winter months, these effects are greatly reduced during summer operation and the pond(s) would contribute little to reducing the load on the primary cooling system. Even during the winter, the exit temperature of the condenser water is limited by the pond temperature and additional cooling would be necessary.

The effect of pond depth on the thermal response of the pond to diurnal changes is shown in Fig. 17 for a day in mid-July. Due to an increase in heat capacity the thermal response of the pond becomes more stable with increasing depth, although even for d = 2 m diurnal temperature variations rarely exceed 2°C. Algal basins, whose depths are typically less than 1 m, would experience larger variations, but this instability would have the desirable effect of increasing yields. In particular, lower nighttime temperatures would reduce respiration rates, thereby increasing algal biomass production.

SUMMARY

The thermal response and control of a shallow pond which utilizes waste heat in a closed cycle cooling system have been considered. Waste heat dissipation and thermal control are implemented by means of a pipe network (an indirect contact heat exchanger), which provides for separation between the pond water and the condenser cooling water. Calculations based on representative models have led to the following conclusions.

(1) The maintenance of a clean outer surface for the pipes is essential to efficient operation. Without such maintenance, the use of an indirect contact heat exchanger becomes impractical.

(2) A heat exchanger design which provides a suitable compromise between initial costs and performance is one which involves a single-pass, counter-flow arrangement (Fig. 2) of one inch diameter, 30 m long pipes with a spacing of 0.15 m. With such a design it is possible to maintain near-optimum pond temperatures throughout the year for climatic conditions typical of the midwest.

(3) The only viable option for regulating thermal conditions within the pond is through control of the flow rate, $\dot{m}''$, of the condenser effluent diverted to the heat exchanger. However, the extent to which such control may be implemented is limited by pump power requirements and the strong influence of the outside convection coefficient on the total resistance to heat transfer. Flow rates in the

range $0.02 \lesssim \dot{m}'' \lesssim 0.04$ kg s^{-1} m^{-2} are recommended.

(4) The extent to which the waste heat utilization system can provide for heat dissipation is limited, and heavy reliance must still be placed on a primary heat sink.

Although the technical feasibility of an indirect contact heat exchanger has been demonstrated, its implementation will depend largely on economic factors. A careful economic analysis should be performed, in which the initial and operating costs of the system are weighed against the economic benefits to be derived from the waste heat utilization process.

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NOMENCLATURE

C'	installation cost per unit length of pipe, \$ m^{-1}
C''	installation cost per unit area, \$ m^{-2}
c_p	specific heat of water, J kg^{-1} K^{-1}
D_c	outer diameter of pipe coating, m
D_i	pipe inner diameter, m
D_o	pipe outer diameter, m
d	pond depth, m
f	pipe friction factor
Gr	Grashof number
h_i	inside pipe convection coefficient, W m^{-2} K^{-1}
h_o	outside pipe convection coefficient, W m^{-2} K^{-1}
k_c	thermal conductivity of coating on outer pipe surface, W m^{-1} K^{-1}
k_w	thermal conductivity of water, W m^{-1} K^{-1}
L	pipe length, m
L''	total pipe length required per unit pond surface area, m m^{-2}

$\dot{m}$	mass flowrate of water through a single pipe, kg s^{-1}
$\dot{m}''$	mass flowrate of water per unit pond surface area, kg s^{-1} m^{-2}
N''	number of pipes per unit pond surface area, m^{-2}
Pr_w	Prandtl number of water
P_L	power required to pump water through a single pipe of length L, W
P''	pump power required per unit pond surface area, W m^{-2}
p	pressure, N m^{-2}
q_L	heat transfer from a pipe of length L, W
$q''_{a,inc}$	incident long-wave atmospheric radiation, W m^{-2}
$q''_{a,ref}$	atmospheric radiation reflected off the air-water interface, W m^{-2}
q''_c	convection of sensible energy from the air-water interface, W m^{-2}
q''_d	rate of heat dissipation from the submerged pipes to the pond, W m^{-2}
q''_{em}	radiation emitted by the pond surface, W m^{-2}
q''_{ev}	convection of latent energy due to evaporation from the air-water interface, W m^{-2}
$q''_{s,inc}$	incident solar radiation, W m^{-2}
$q''_{s,ref}$	solar radiation reflected off the air-water interface
R_c	thermal resistance of coating on outer pipe surface, m K W^{-1}
Re_D	Reynolds number of the pipe internal flow
R_i	inside convection resistance, m K W^{-1}
R_o	outside convection resistance, m K W^{-1}
R_t	total thermal resistance per unit length of pipe, m K W^{-1}
S	spacing between pipe centers, m
T	pipe water temperature, K
T_i	pipe inlet (condenser discharge) water temperature, K
T_o	pipe outlet water temperature, K

T_p	pond water temperature, K
t	time, s
V	velocity of water in the pipes, m s^{-1}
x	coordinate along the pipe axis, m
ε	heat exchanger effectiveness
ρ	mass density of water, kg m^{-3}

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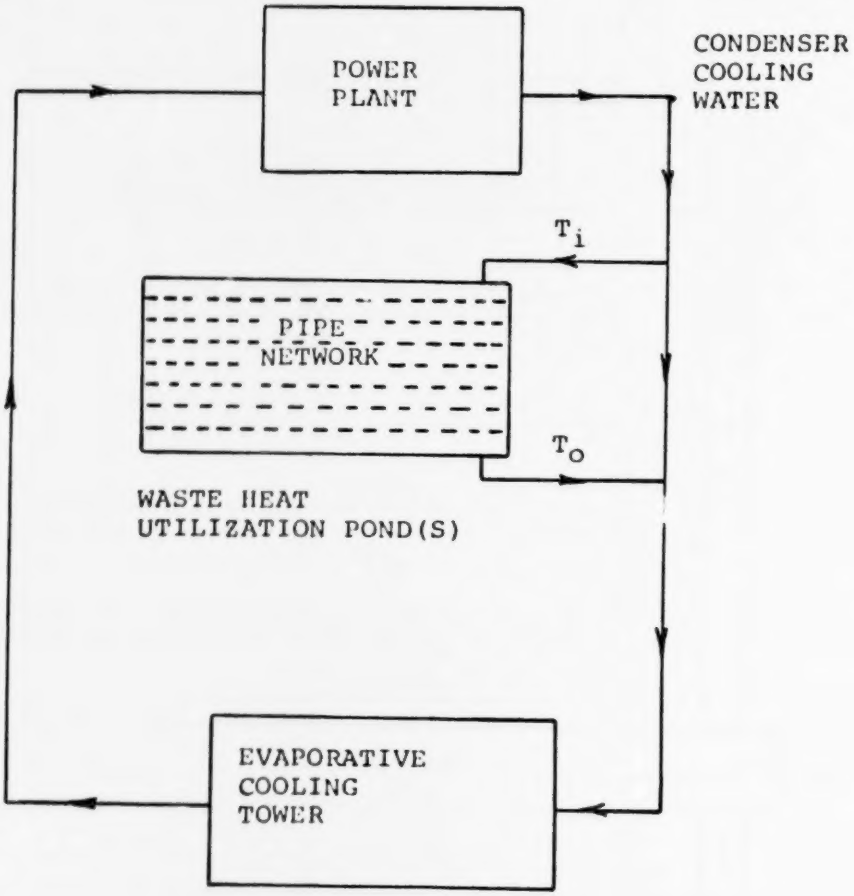
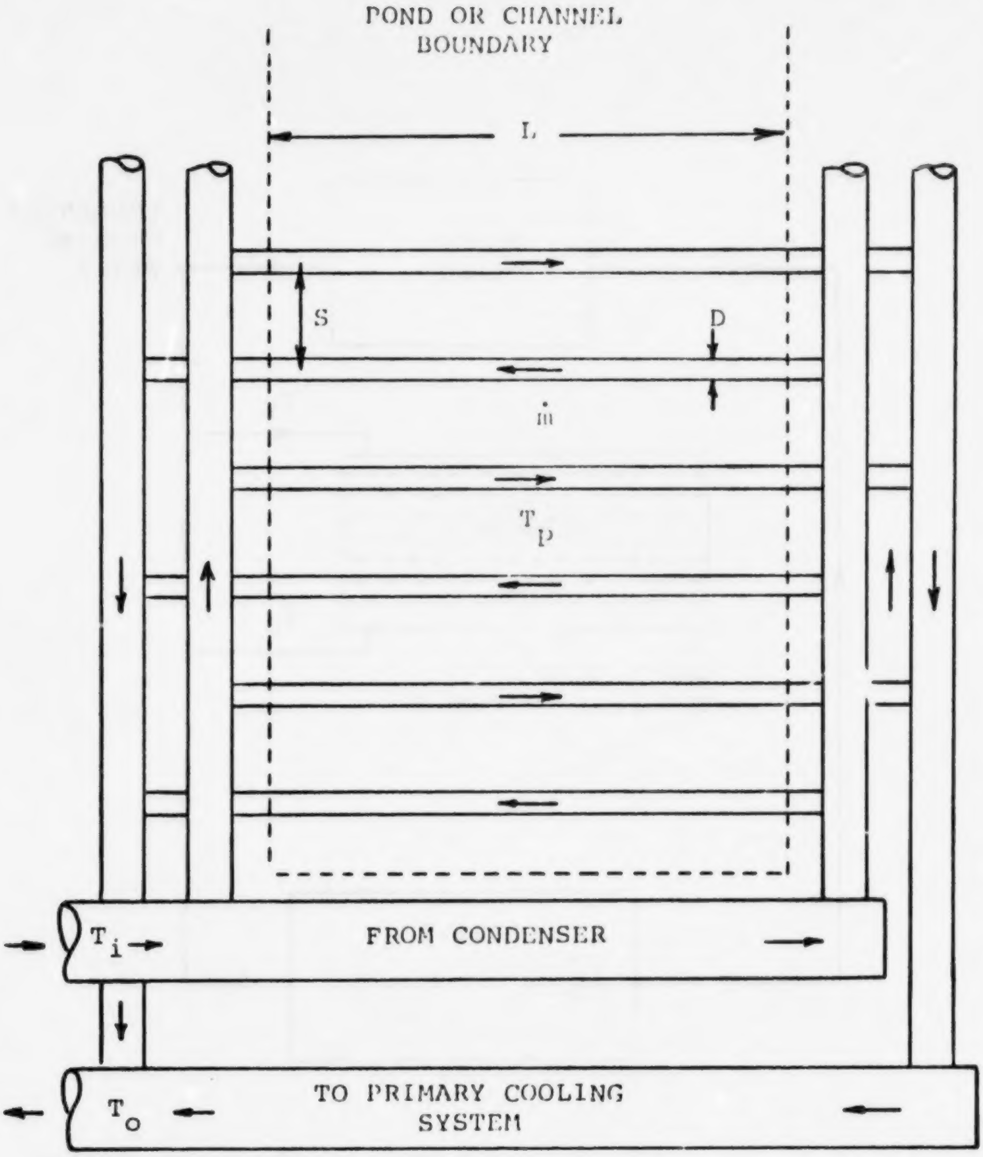

POWER PLANT
CONDENSER COOLING WATER
T_i
PIPE NETWORK
T_o
WASTE HEAT UTILIZATION POND(S)
EVAPORATIVE COOLING TOWER

Figure 1 Closed Cycle Waste Heat Utilization System.


POND OR CHANNEL BOUNDARY
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FROM CONDENSER
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TO PRIMARY COOLING SYSTEM

Figure 2 The Pipe Network Heat Exchanger.

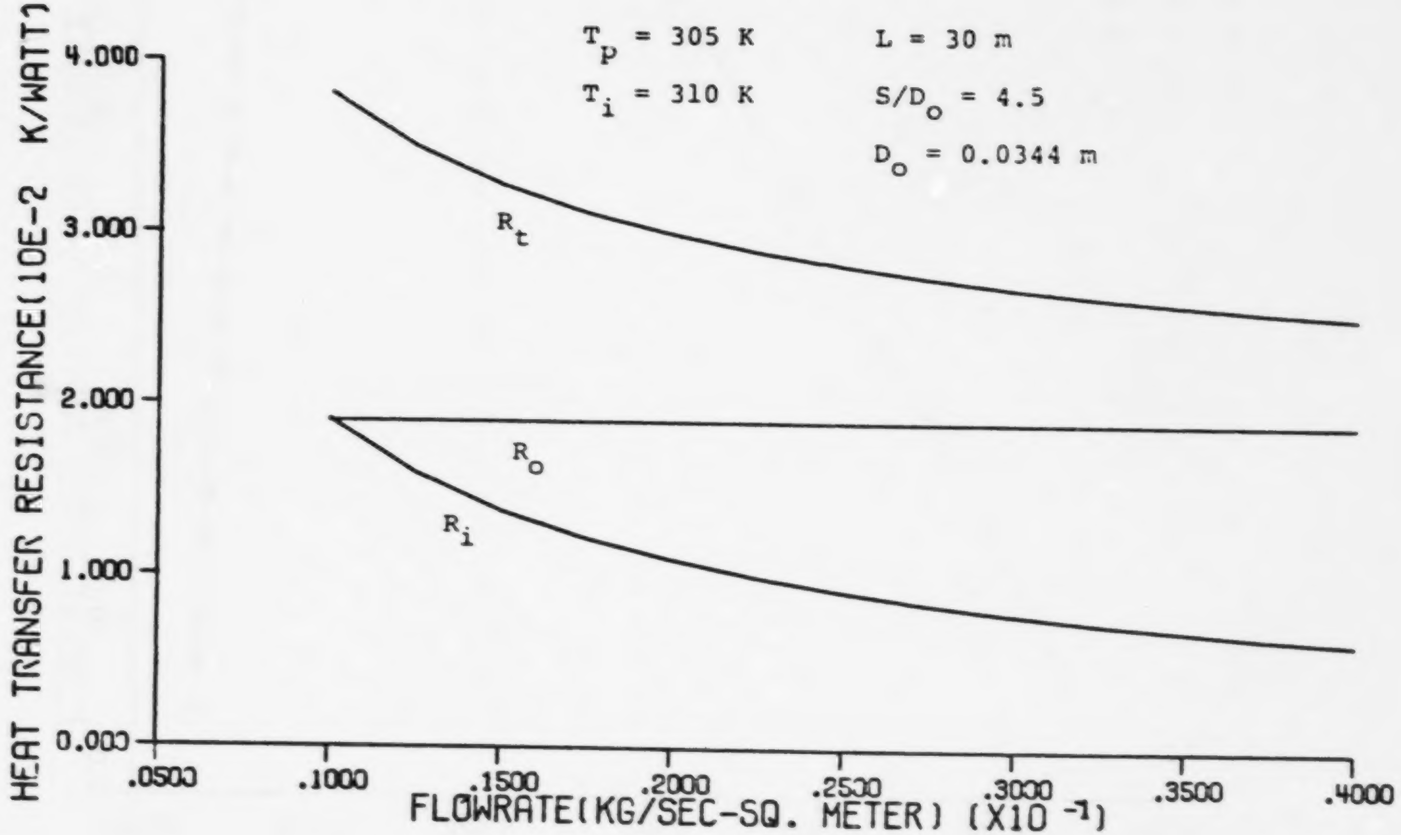

Figure 3 Inside Convection Resistance, R_i, as a Function of Flowrate, $\dot{m}''$.

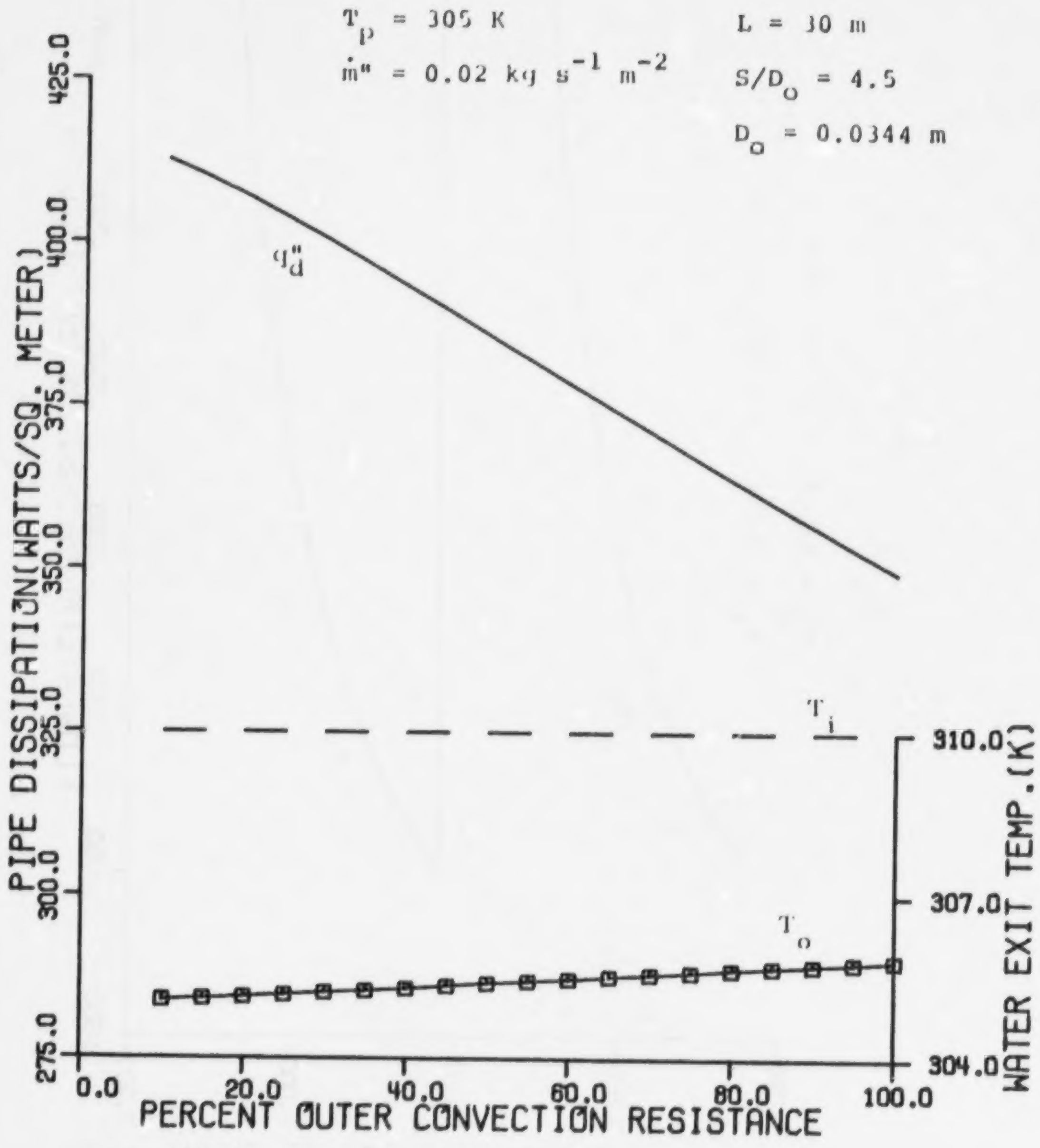

Figure 4 Effect of Outer Convection Resistance, R_o, on Heat Dissipation, q_d'', and Outlet Temperature, T_o.

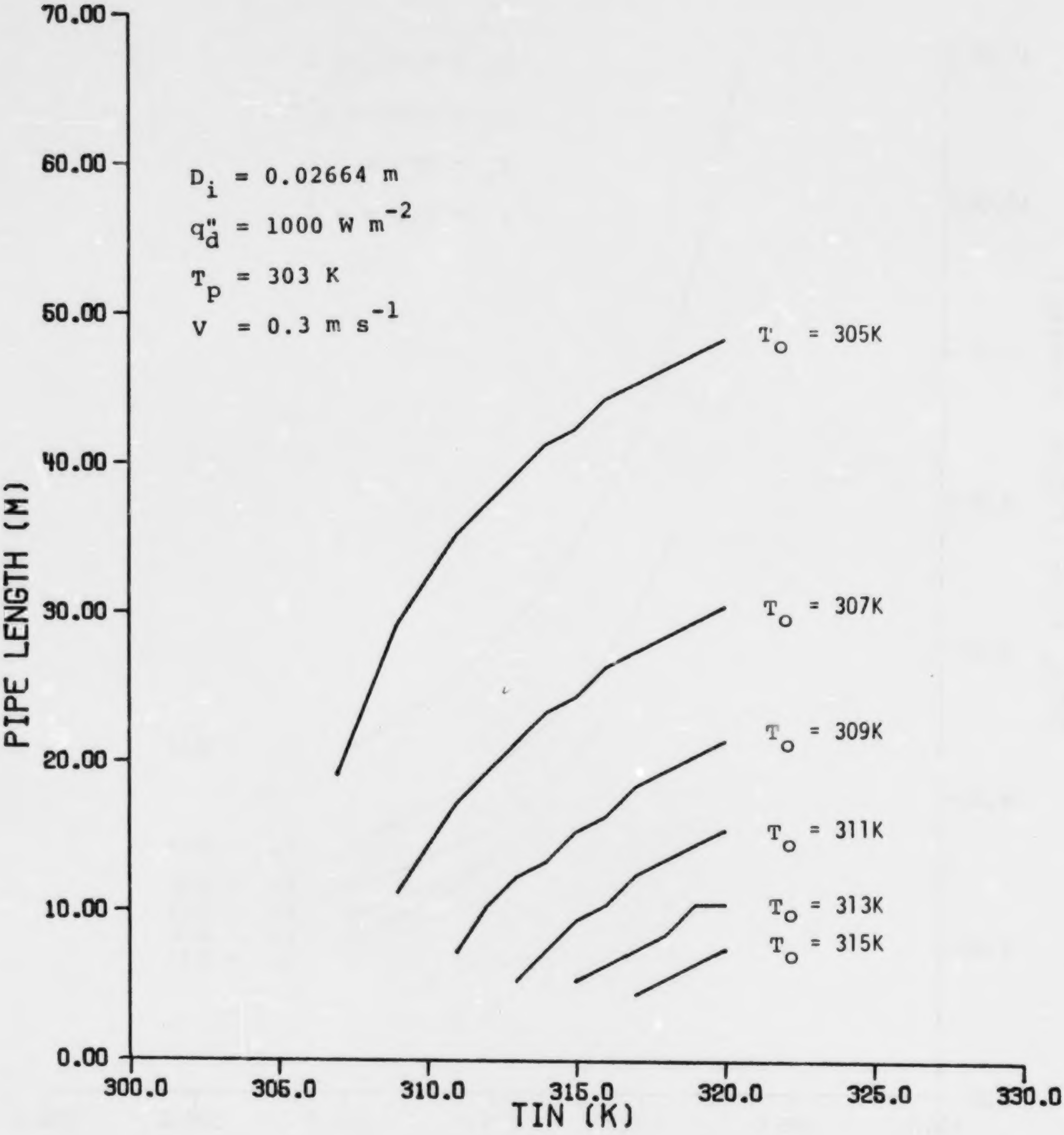

Figure 5 Pipe Length, L, as a Function of Inlet, T_i, and Outlet, T_o, Temperatures.

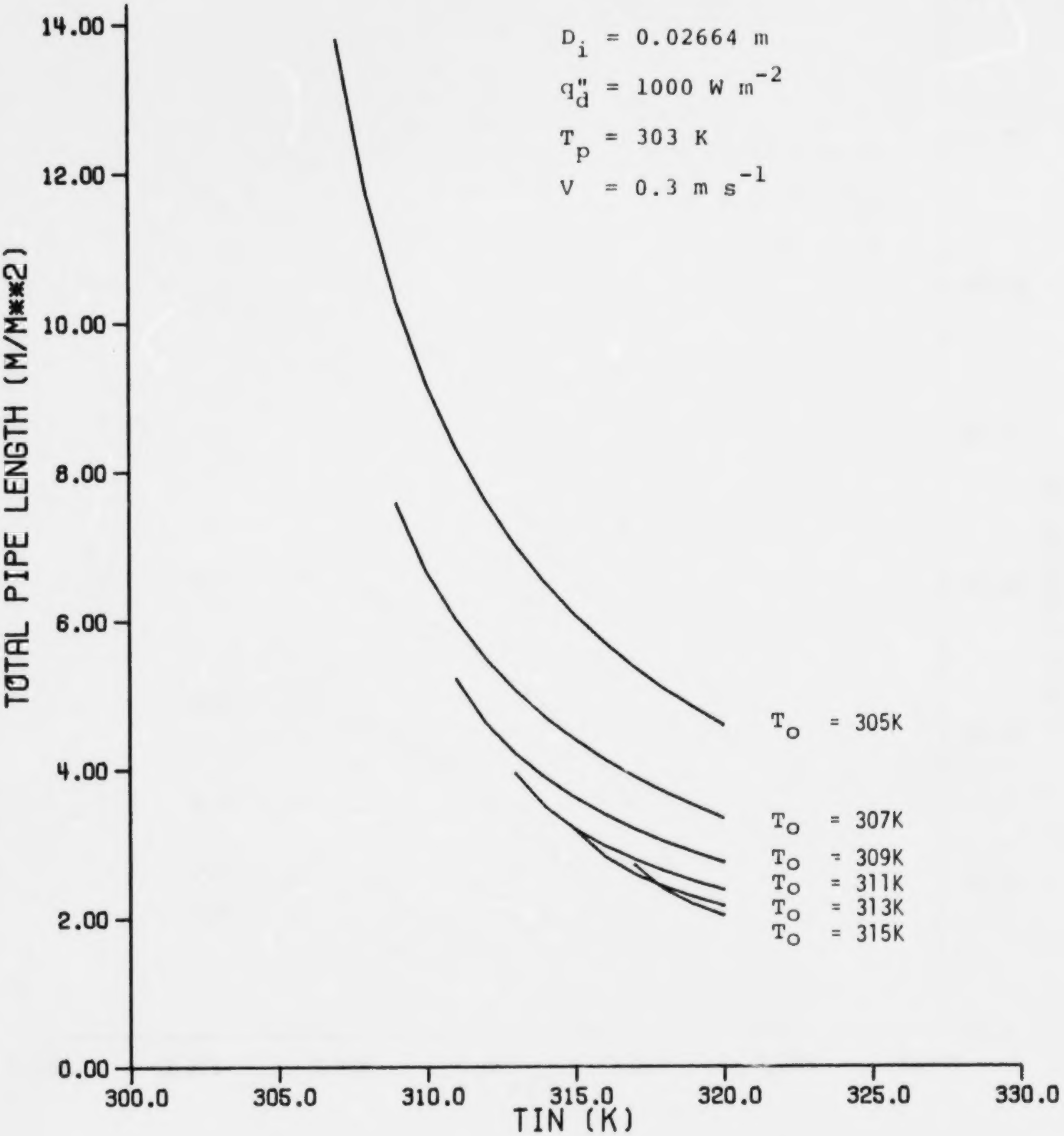

Figure 6 Total Pipe Length, L", as a Function of Inlet, T_i, and Outlet, T_o, Temperatures.

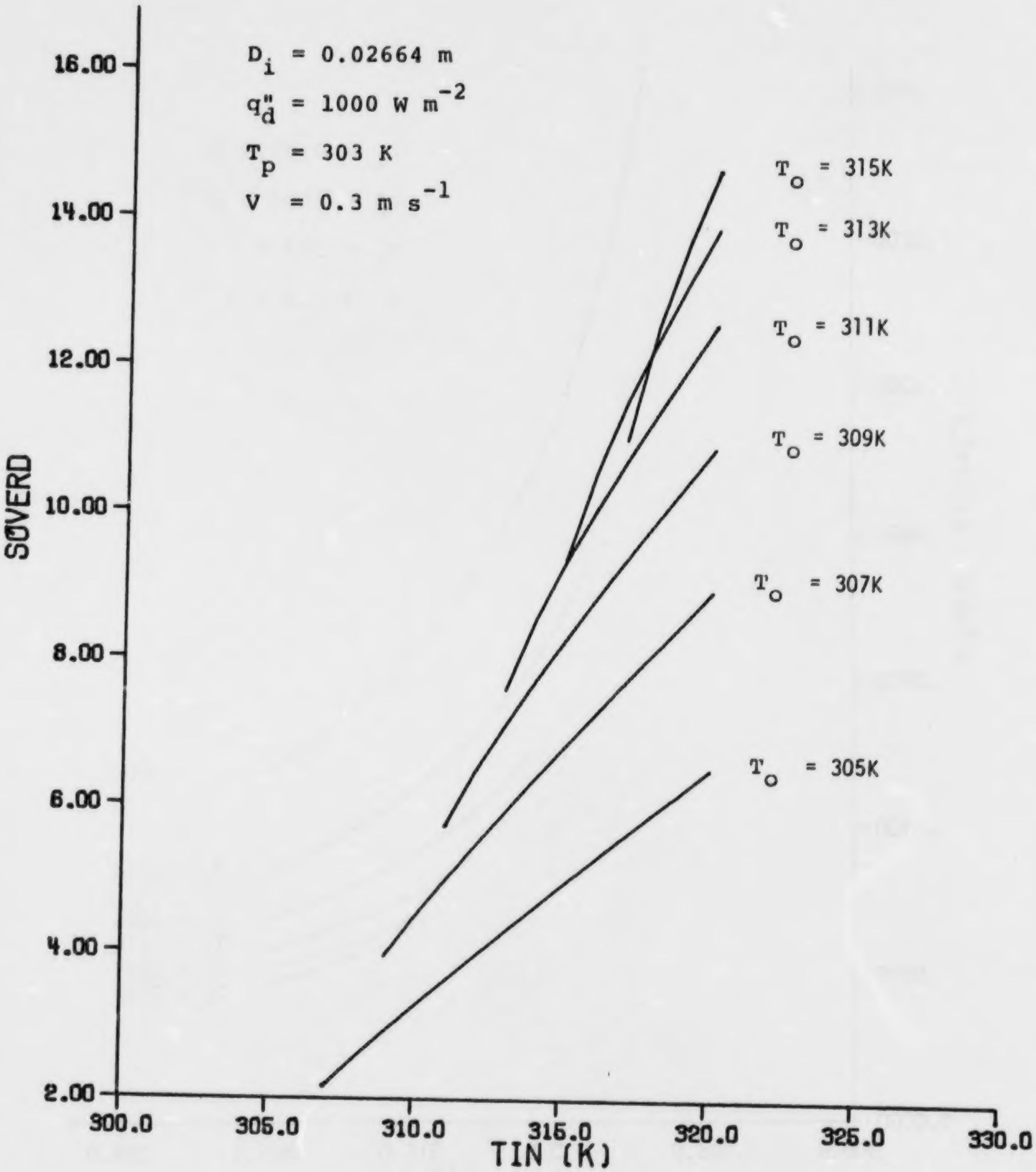

Figure 7 Pipe Spacing to Diameter Ratio, S/D_o, as a Function of Inlet, T_i, and Outlet, T_o, Temperatures.

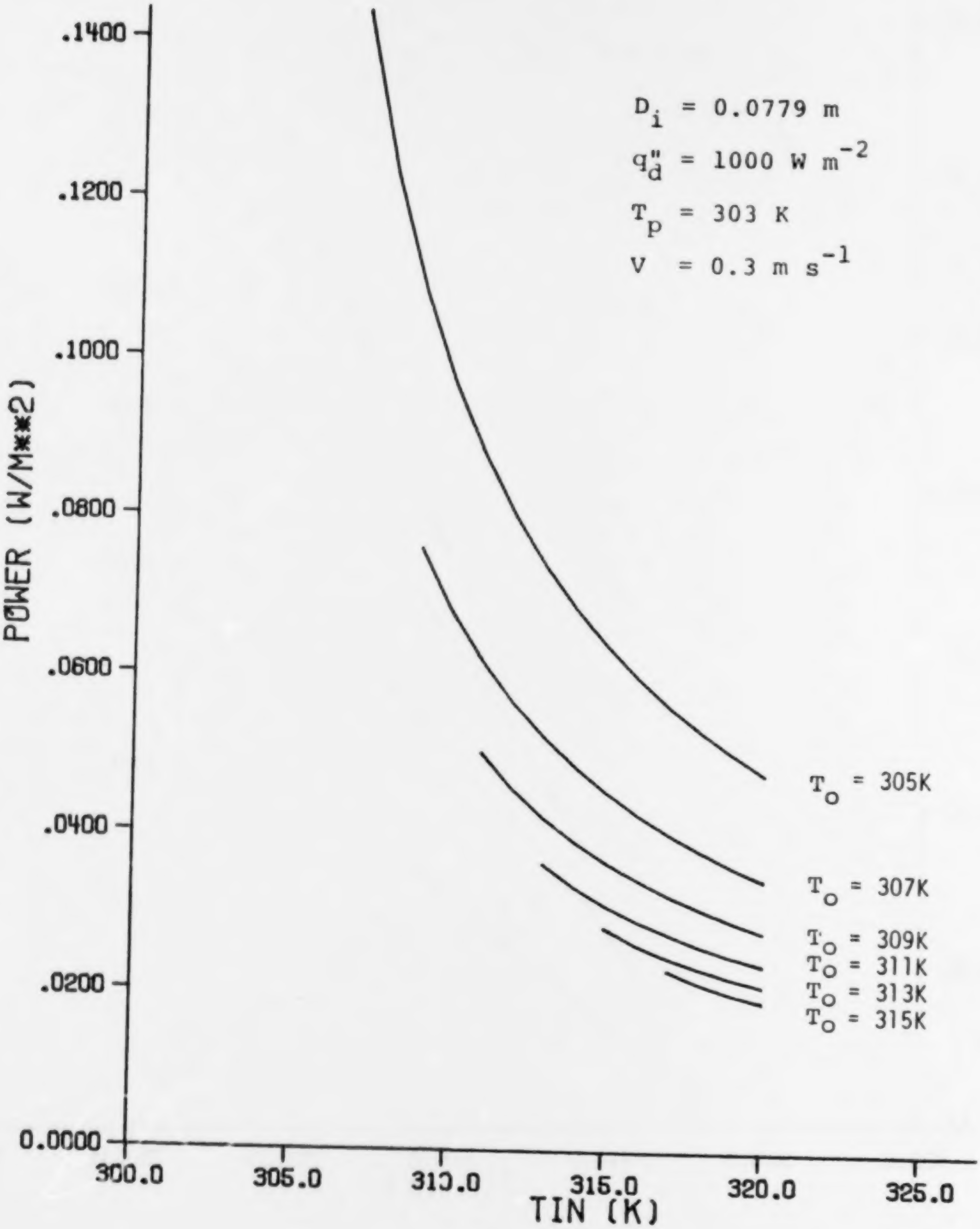

Figure 8 Pump Power, P", as a Function of Inlet, T_i, and Outlet, T_o, Temperatures.

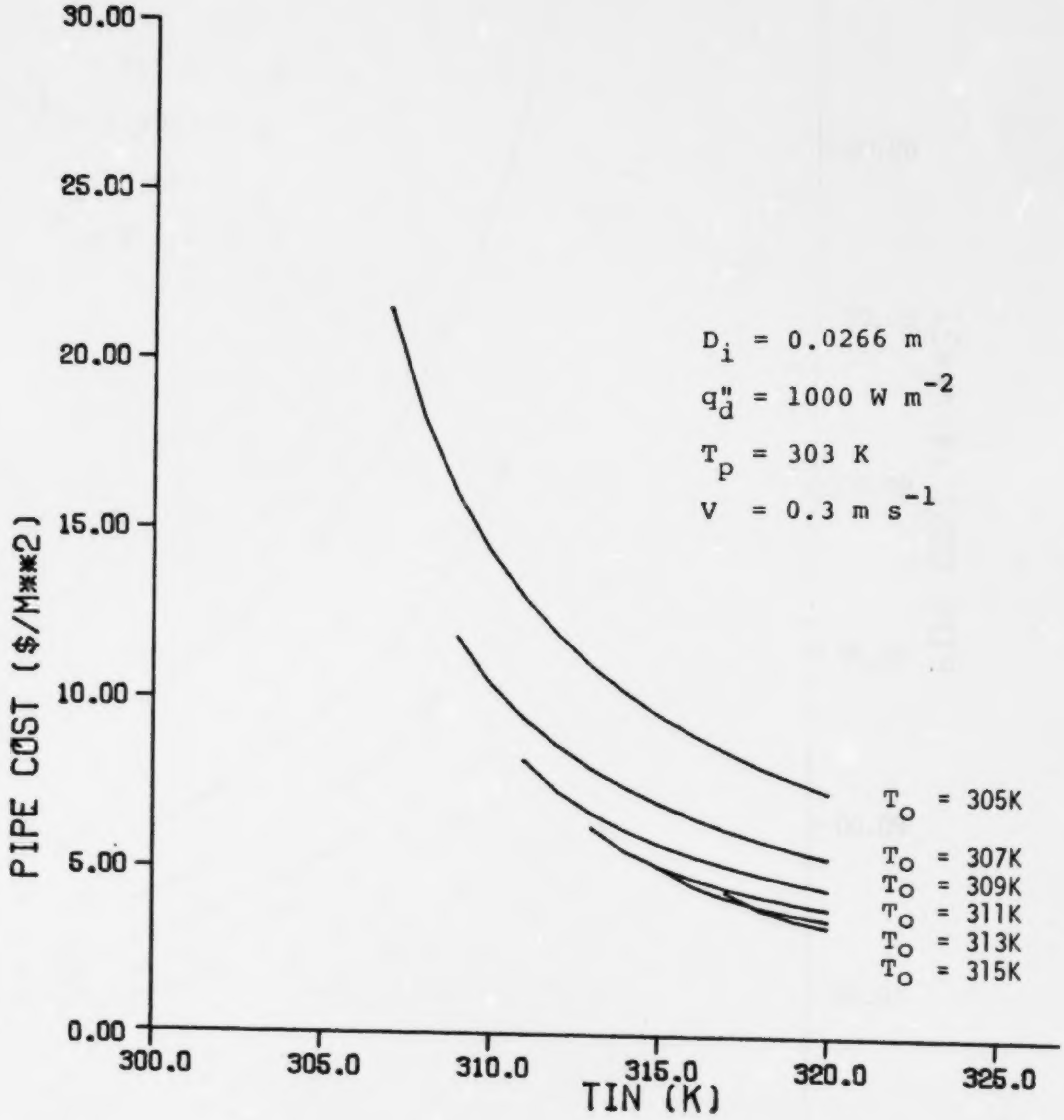

Figure 9 Pipe Cost, C", as a Function of Inlet, T_i, and Outlet, T_o, Temperatures (D_i = 0.0266 m).

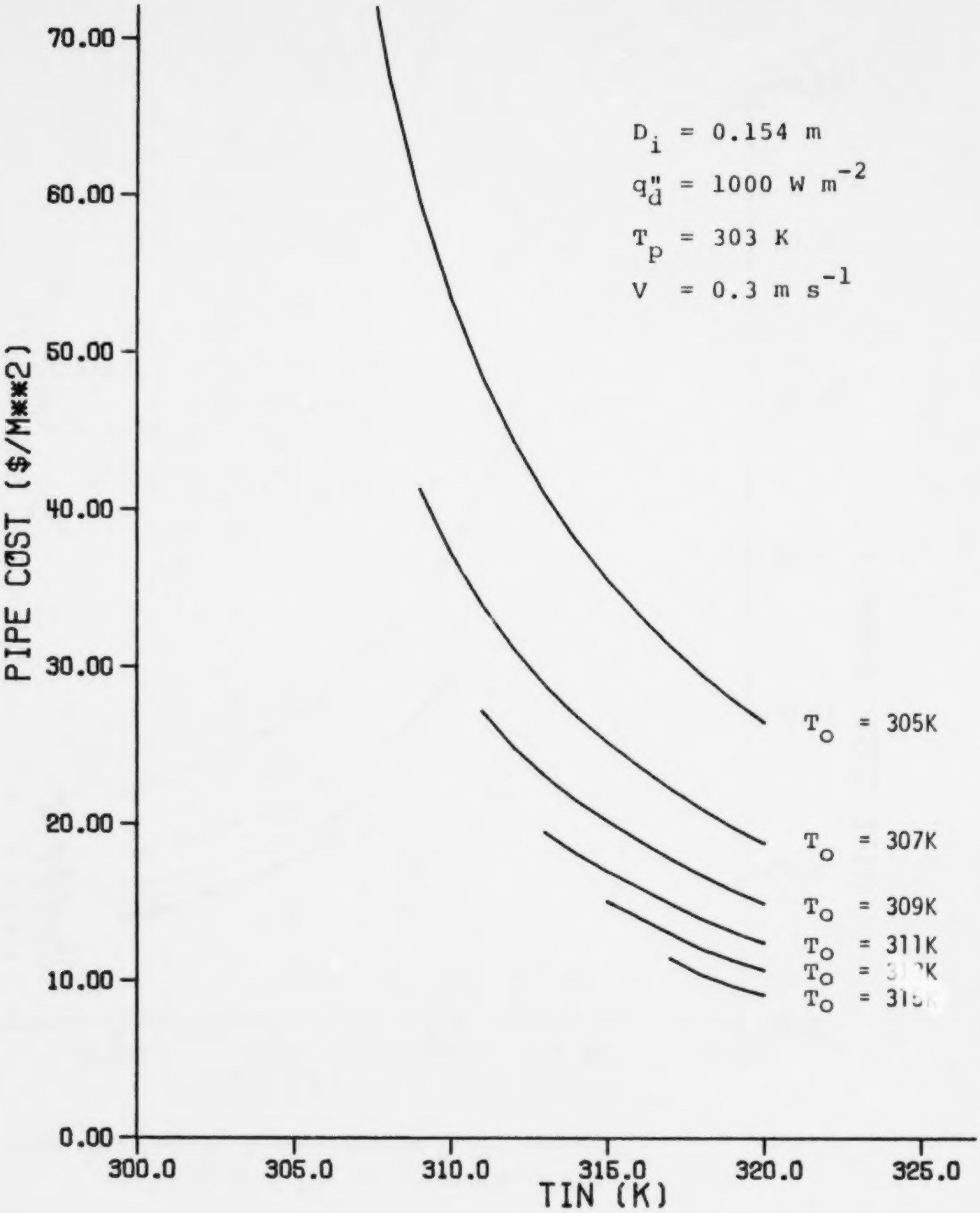

Figure 10 Pipe Cost, C", as a Function of Inlet, T_i, and Outlet, T_o, Temperatures (D_i = 0.154 m).

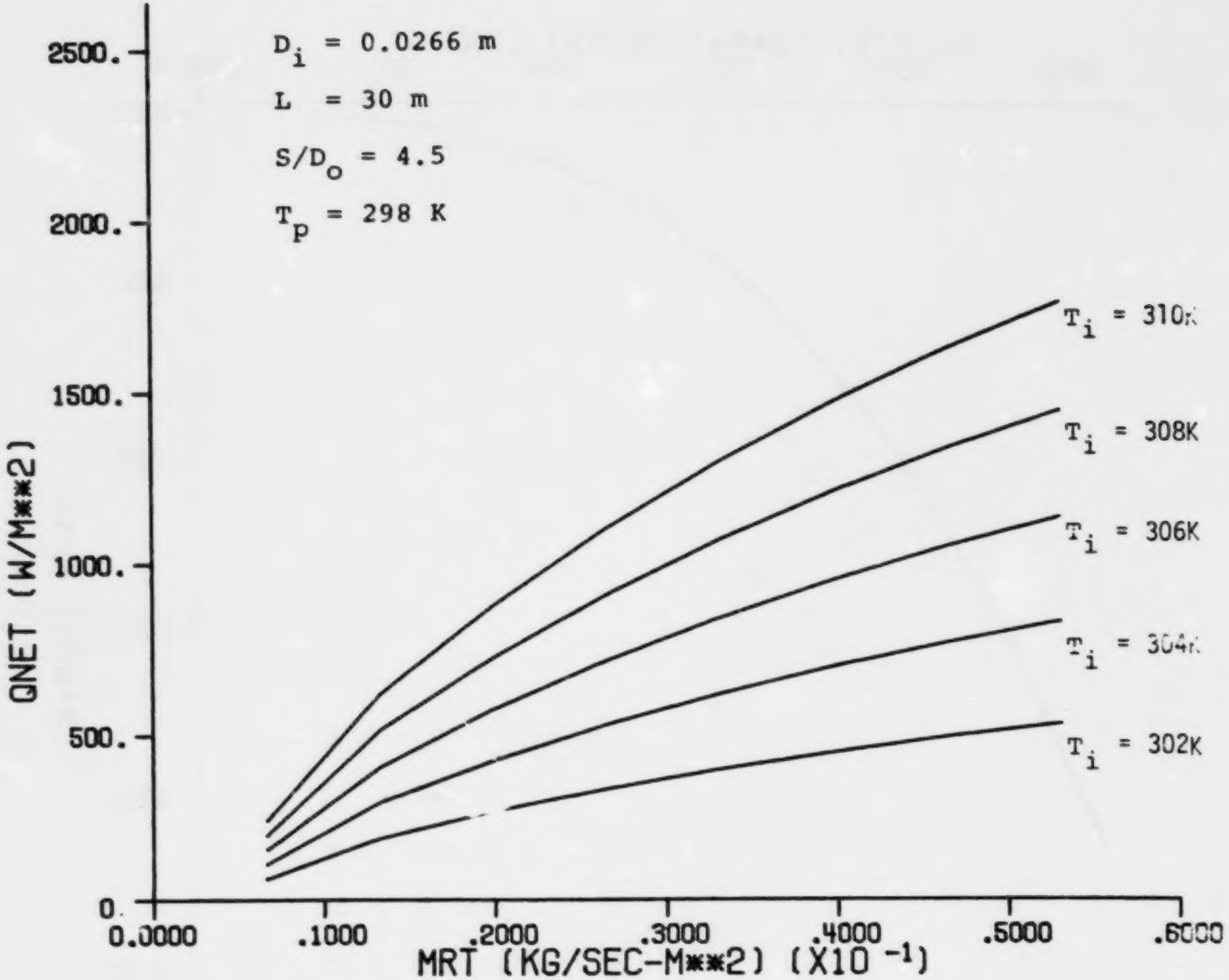

Figure 11 Heat Dissipation, q''_d, as a Function of Inlet Temperature, T_i, and Mass Flowrate, $\dot{m}''$.

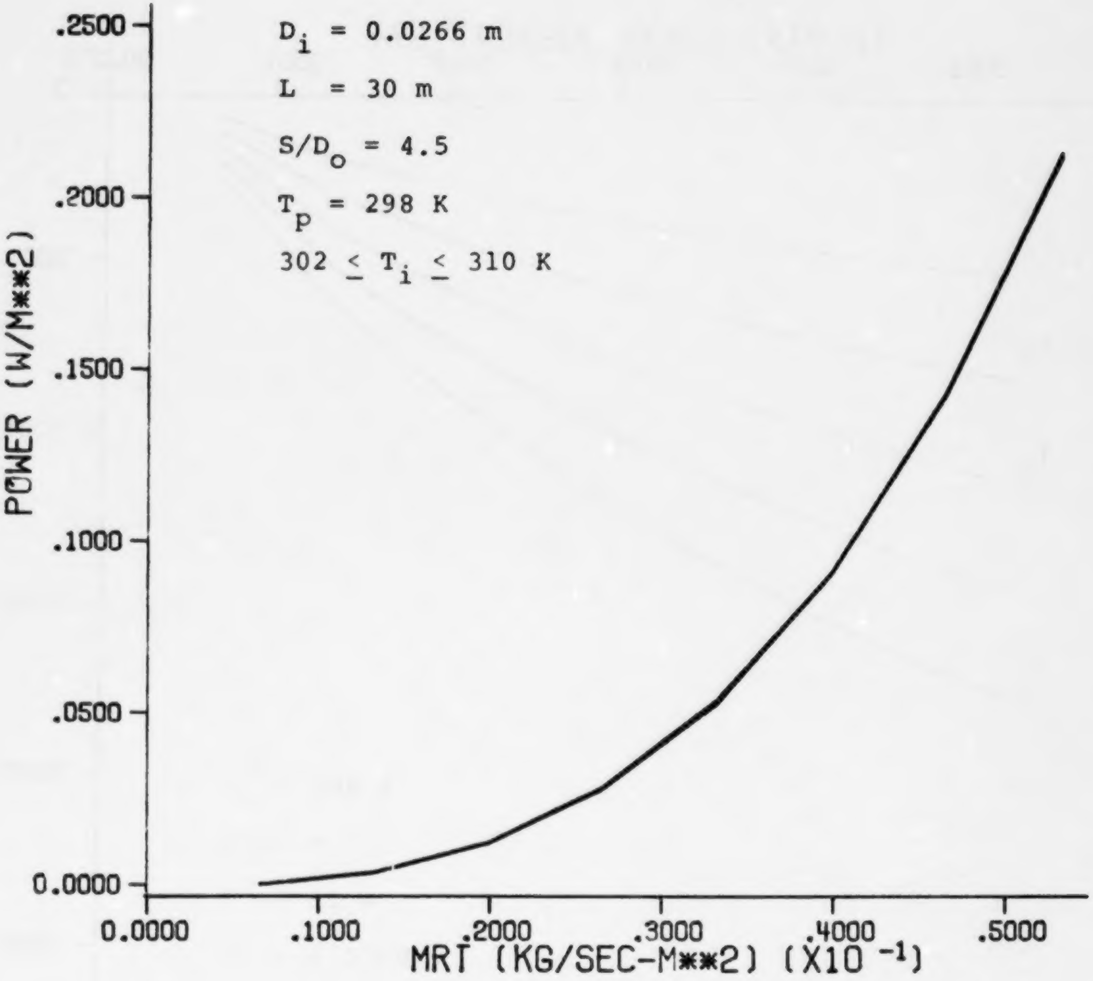

Figure 12 Pump Power, P", as a Function of Mass Flowrate, $\dot{m}$".

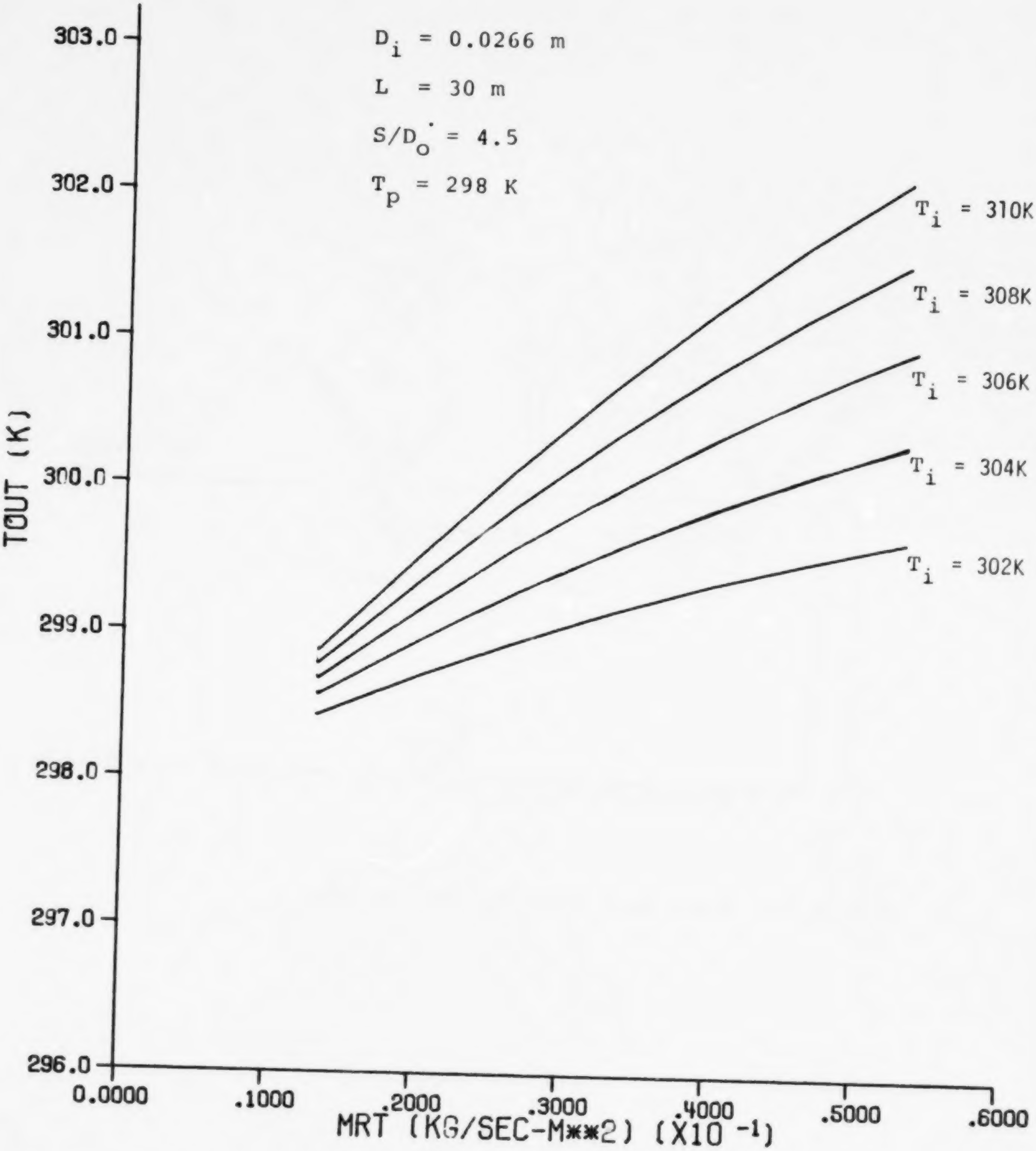

Figure 13 Outlet Temperature, T_o, as a Function of Inlet Temperature, T_i, and Mass Flowrate, $\dot{m}''$.

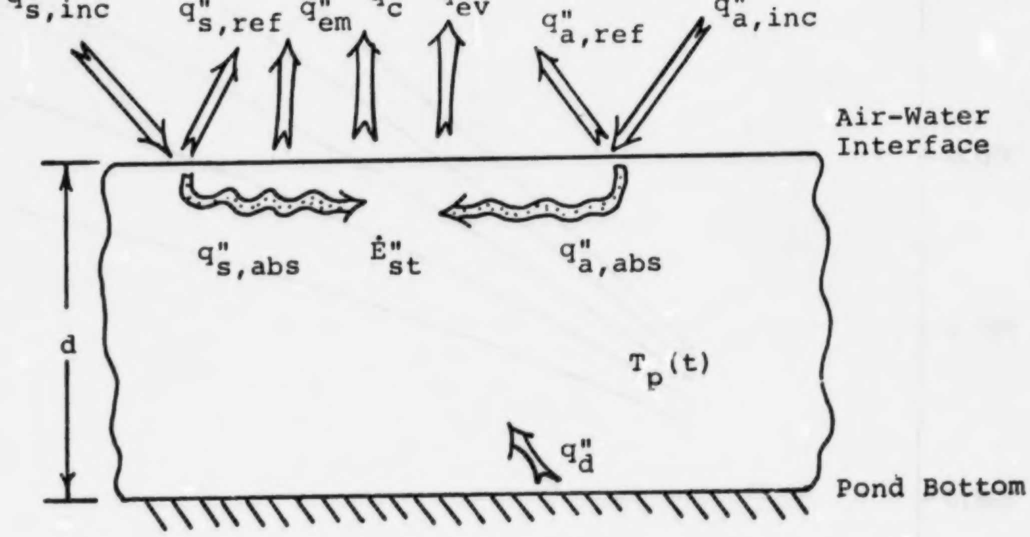
$q''_{s,inc}$
$q''_{s,ref}$
q''_{em}
q''_{c}
q''_{ev}
$q''_{a,ref}$
$q''_{a,inc}$
Air-Water Interface
$q''_{s,abs}$
$\dot{E}''_{st}$
$q''_{a,abs}$
d
$T_p(t)$
q''_d
Pond Bottom

Figure 14 Pond Heat Exchange Mechanisms.

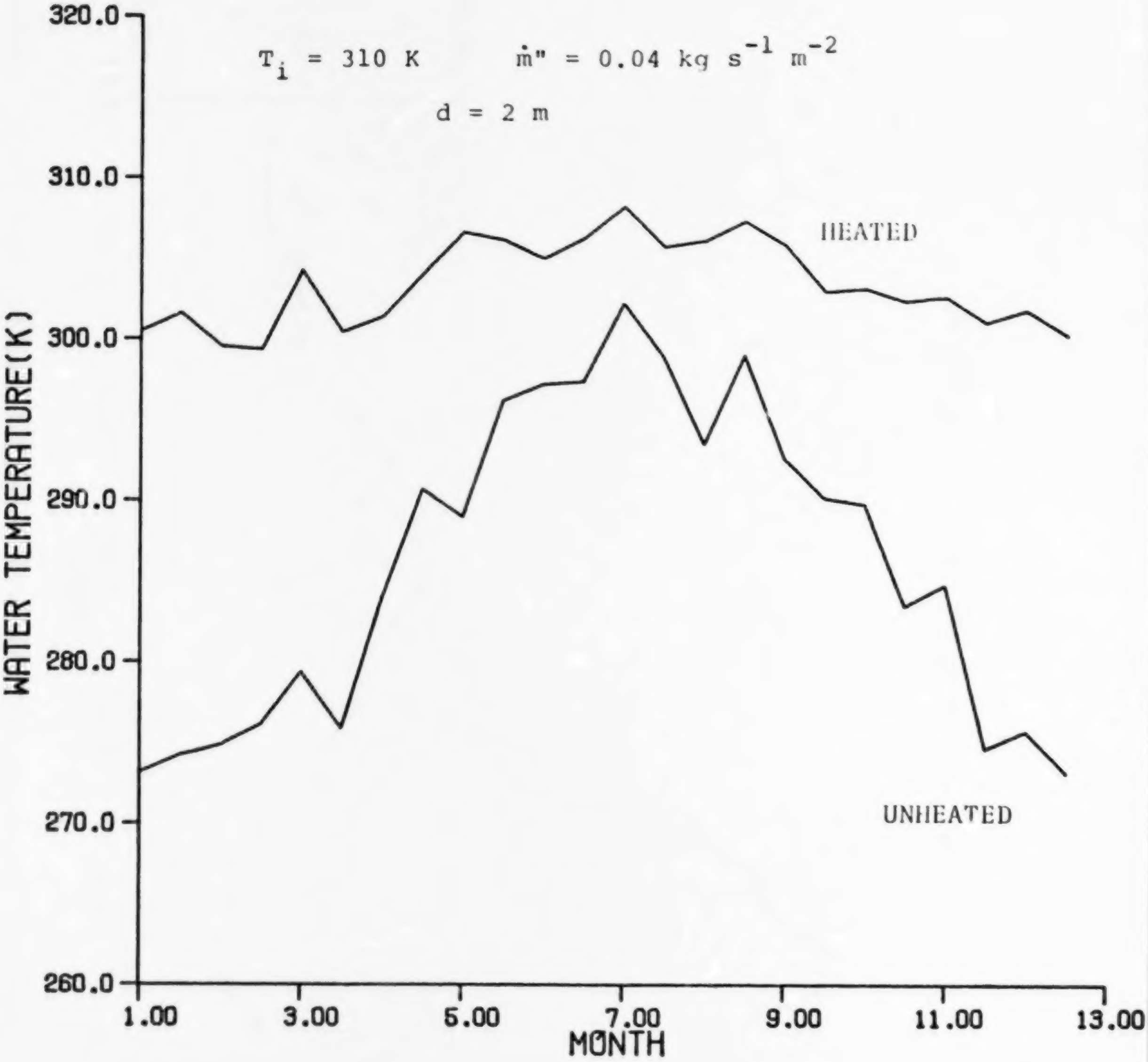

Figure 15 Pond Thermal Response for the Heated and Unheated Conditions (Indianapolis, Indiana, 1974).

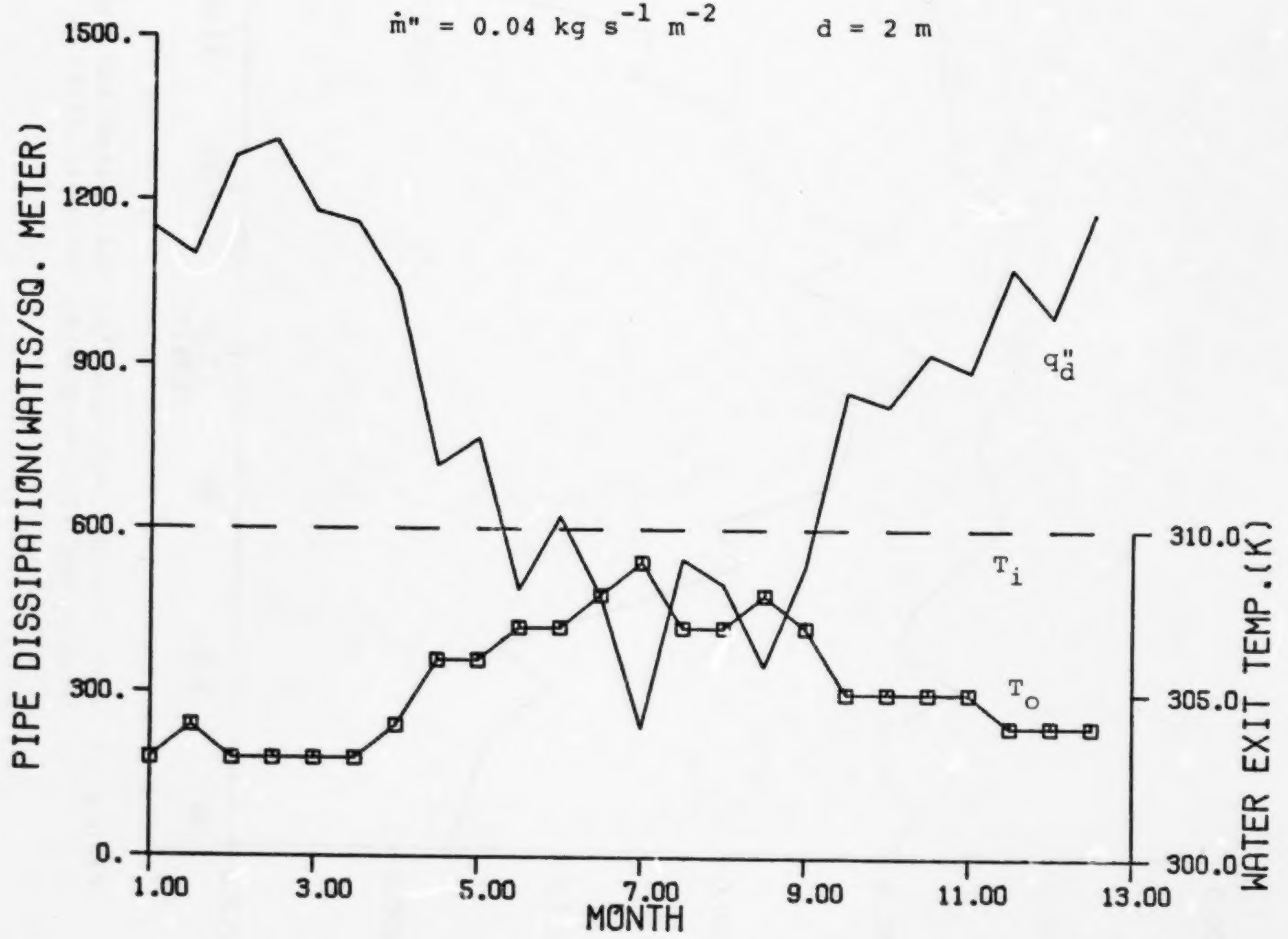

Figure 16 Seasonal Variation of the Heat Dissipation, q''_d, and Outlet Temperature, T_o, of a Heated Pond (Indianapolis, Indiana, 1974).

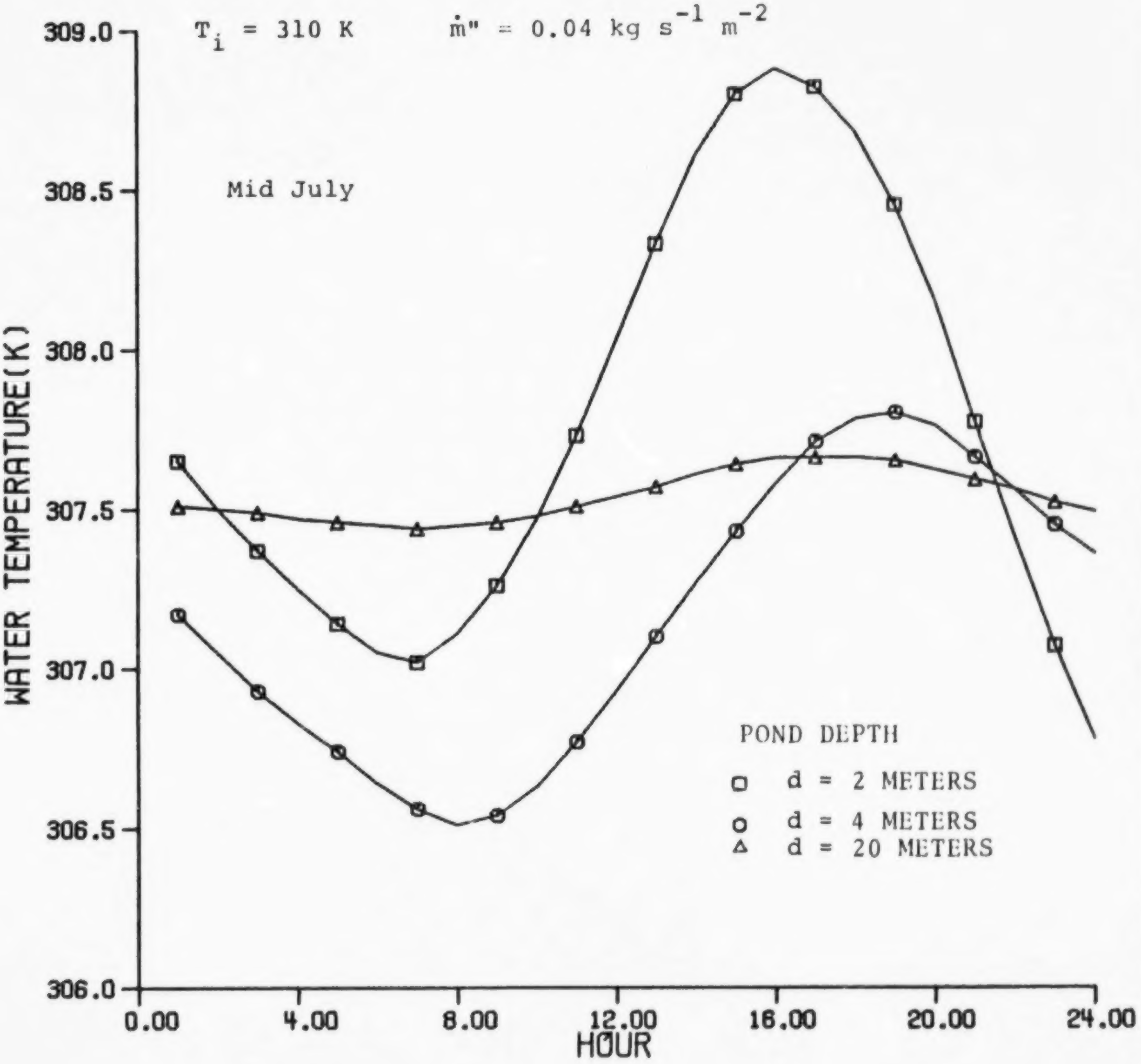

Figure 17 Diurnal Variation of Pond Temperature, T_p, as a Function of Pond Depth, d (Indianapolis, Indiana, 1974).

VIII-A-131

The Agrotherm Research Project

H. Luckow

Thyssen House
Dusseldorf, Germany

Session VIII B

Physical Models

5-45-21

VIII-B-135

THE DISCHARGE OF A SUBMERGED BUOYANT JET INTO A STRATIFIED ENVIRONMENT

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ABSTRACT

In order to determine the nature of offshore (deep-water) disposal of waste heat, consideration is given to the dispersion of a single round turbulent buoyant jet entering into a highly stratified receiving water. Measurements are performed on a laboratory model of this phenomenon, employing salt solutions and photographing trajectories of the dyed jet for a range of angles above the horizontal of 0, 30, 45, and 90°, and for entrance Reynolds numbers from 450 to 2030, in linear stable density gradients of 0.7×10^{-3} and 1.4×10^{-3} gm/cm^4, a stratification environment greater than in existing work.

The terminal height of rise of the jet, when scaled with the characteristic length Y_F, the distance above the entering jet at which the ambient stratified density is that of the jet at entrance, is found to depend on the densimetric Froude number based on Y_F and the injection angle, as long as the jet enters turbulently, the free surface height above the entering jet is greater than Y_F, and the stratification parameter, the ratio of Y_F to the entrance diameter of the jet, is large.

INTRODUCTION

The large quantities of waste heat discharged into large bodies of water from existing thermal and future nuclear power plants pose serious environmental problems. At least for the present the primary concern is not that entire lakes will become thermally polluted but that the pollution will be concentrated over certain important parts of the shorelines. This view is obtained from models based on inshore and surface discharge of the effluents. There are, however, other ways in which the waste heat can be discharged, e.g., hypolimnetically. This option has received relatively little attention and the present paper represents the initial phase of an investigation to obtain qualitative and detailed information on the flow phenomena associated with hypolimnetic discharge of hot effluents.

Deep-water discharge of waste heat appears to have a number of attractive features. Much greater volumes of the open water would be available for absorption of the heat. Also, the introduction of the hot effluents deep in lakes could at low Froude numbers induce a thermal instability due to heavier water being above lighter water. Such a thermal instability can generate strong mixing flows, at least, locally. Thus, normal lake currents could be altered in this way and perhaps, more importantly, significant lake currents could be generated during periods when the lake is normally stably stratified and, therefore, essentially stagnant. These induced flows could be beneficial for the dissipation of waste heat. Furthermore, when the lake is stratified and stagnant there is a serious problem of dissolved oxygen depletion due to the oxidation of organic carbon in the hypolimnion waters. Disruption of the stratification by the deep-water disposal of waste heat would provide mixing to alleviate or eliminate the oxygen depletion problem and would, therefore, be ecologically beneficial.

The present study is intended to obtain some physical insight into the flow phenomena involved with deep-water discharge of hot effluents into stably stratified water. Basic to understanding the flow phenomena of submerged discharges is the behavior of single round buoyant jets ejected into stratified receiving water.

One of the first analyses of buoyant jets into a stratified environment was performed by Morton [1]. He utilized an integral method to study a vertical axisymmetrical jet in a linearly density-stratified fluid. Fox [2] studied the same problem in the same way with different assumptions. Mangarella and Van Dusen [3] also used an integral technique and an entrainment formula to calculate plume trajectories and centerline temperatures. Most of their work is for horizontal effluent discharge. Experimental and analytical studies of inclined turbulent buoyant jets discharged into stagnant stratified environments were presented by Fan [4]. His analysis was also like Morton's and the calculations of the jet behavior were presented as a function of two dimensionless parameters, viz., the densimetric Froude number, F, and the stratification number, S, defined as:

$$F = \frac{U}{(\Delta\rho g D/\rho_j)^{1/2}} \quad \text{and} \quad S = \frac{\Delta\rho}{\gamma D}$$

where U is the jet exit velocity, $\Delta\rho$ the initial density difference at the discharge point, D the jet diameter, g is the acceleration of gravity, ρ_j the jet density, and γ is the vertical (stratified) density gradient. For the most part Fan's work is limited to relatively weak stratifications. For deep-water discharge of waste heat during the stratification period, however, consideration must be given to large stratifications such as associated with the thermocline.

The present experiments are, therefore, conducted to observe the terminal height of rise of round buoyant jets discharged in stagnant, linearly density-stratified environments where the stratification is large.

EXPERIMENT DESIGN

In order to obtain a realistic model for experimentation it is necessary to know the dimensionless parameters that describe the actual phenomena. To this end these parameters are derived below.

Dimensionless Parameters

Consider a fluid particle that is discharged from an inclined jet into a stable and stagnant linearly density-stratified environment, Fig. 1. Assume steady flow and no mixing between the jet and the environment. Conservation of momentum in the vertical direction yields the velocity in the vertically upward direction to be,

$$v(y) = \{2(\frac{\rho_o}{\rho_j} - 1)gy - \frac{\gamma g}{\rho_j}\ y^2 + U^2 \sin^2 \theta\}^{1/2}$$

where

$$\rho_a(y) = \rho_o - \gamma y \text{ with } \gamma = |\frac{d\rho_a}{\partial y}|.$$

The horizontal velocity in this simplified model remains constant at U cos θ .

The trajectory can be put in the following form,

$$y/Y_F = 1 - \cos\ (\frac{x/Y_F}{F \cos\theta}) + (F \sin\theta) \sin\ (\frac{x/Y_F}{F \cos\theta}), \qquad (1)$$

where

$$Y_F = \frac{\rho_o - \rho_j}{\gamma},\ F = \frac{U}{[(\frac{\rho_o - \rho_j}{\rho_j}) Y_F g]^{1/2}},$$ i.e., the densimetric Froude number based on Y_F, the modified Froude number.

It is apparent from the foregoing simplified analysis that the significant characteristic length in this problem is

$$Y_F = \frac{\rho_o - \rho_j}{\gamma},$$

the distance above the entering jet at which the surrounding fluid's density equals that of the jet at entrance. This is the vertical location around which the inviscid model of the trajectory oscillates and can be regarded as an upper limit on the terminal height of rise in the actual phenomenon, where mixing damps out the oscillation, dissipates both vertical and horizontal momentum, and causes the jet to settle out at a vertical position less than Y_F. The above analysis also indicates that along with the injection angle, θ, the densimetric Froude number based on Y_F not D, the jet diameter at entrance, is the significant comparison of inertia to buoyancy forces. In particular for the non-mixing, inviscid trajectory equation shown above, the vertical position scaled with Y_F depends solely on the horizontal position suitably scaled with Y_F and the ratio of horizontal momentum to buoyancy induced vertical momentum, and with F sin θ, the ratio of initial vertical momentum to buoyancy induced vertical momentum.

The entrance diameter of the jet, D, is only significant as it effects the entrance Reynolds number of the jet (in this work the jet is forced to be turbulent for all runs except a few which are mentioned separately), so long as the stratification parameter, Y_F/D is large, i.e., the most physically realizable and most interesting case. These arguments are based on the assumption that the free surface height above the entering jet is larger than Y_F so that for all cases measured the free surface does not interfere with the phenomenon. Thus for turbulent jets at entrance, D is not expected to significantly effect the results and more importantly, the stratification parameter, which is large for all runs, is not expected to effect the results, leaving the terminal height of rise when scaled with Y_F to depend only on the modified Froude number, F, and the injection angle, θ, (one may argue that this dependence is more acceptable in the form F sin θ, the ratio of initial vertical momentum to a buoyancy induced momentum, and tan θ, the ratio of the initial vertical momentum to the initial horizontal momentum).

Lake Michigan Model

Now that the relevant nondimensional parameter has been determined its range of values in real situations must be determined so that the experimental apparatus can be designed to model the actual flow phenomena. Lake Michigan is considered to be the prototype both because there exists considerable data on its nature and power input and because it is relatively deep.

Lake Michigan is the sixth largest fresh water lake in the world and has an area of 58015 square kilometers and a shoreline of 2673 kilometers. Maximum depth of the lake is 494 kilometers and its maximum width is 190 kilometers in the northern basin and 120 kilometers in the southern basin. Maximum depth is 281 meters and mean depth is 84 meters. The lake volume is estimated to be 4.9×10^{12} cubic meters.

During the period from June through October the lake is highly stratified with a layer of sharp vertical temperature gradient called the thermocline (see Huang [5]).

Consider a 1000 megawatt nuclear power plant with a typical condenser water flow rate of 42.48 cubic meters per second. For a pipe diameter of 4.57 meters and a temperature rise of 11°C for the water passing through the condenser the modified Froude number is approximately 2. Thus, for the present investigation the modified Froude number, F, varies from 0.79 to 3.6. With the experimental apparatus it is not possible to match the model and prototype Reynolds numbers. The model Reynolds numbers are several orders of magnitude smaller than in the actual field case because of the reduced scale of the model. It is then assumed that it is sufficient to have a Reynolds number large enough to insure turbulent flow in the model.

The Experimental Facility

The experiments are performed in a laboratory water tank filled with density stratified fluid. The tank is 1.83 meters long, 1.8 meters wide, and 19.05 centimeters deep. One side of the tank is made of .64 centimeters thick plexiglass so that photographs can be taken through it. The tank is filled with water with varying salt concentration to produce the stratification. The overall experimental arrangement is shown in Fig. 2.

The variation of density is obtained by mixing salt and fresh water in different proportions. Tap water is used as the base fluid. The fluid temperature is between 18 and 20°C for all experiments.

The procedure for filling the tank followed the method described by Koh [6]. At first, a stock solution of NaCl with a density of 1.2 gm/cc is prepared. The amounts of salt necessary to produce 45.4 liters of solution with the desired densities are computed and the corresponding volumes of stock solution are determined. These volumes of stock solution are then mixed with fresh water in a 45.4 liter container to produce solutions of desired densities. The densities are checked by a calibrated hydrometer. The contents of the container are then introduced into the tank through a rubber tube onto a floating filling device This device is shown schematically in Fig. 3. The fluids added in this manner spread out horizontally with the lighter layers above the heavier ones. Twelve layers of water of different densities but equal volumes fill the tank to a depth of 16.83 cm. The resulting density profiles are not step-like because of molecular diffusion as well as some mixing introduced by the disturbances due to filling. The density profiles were allowed to smooth out before the experiments were conducted. Two different density gradients, $(1/\rho_1)(d\rho_a/dy) = (1.4 \pm 0.07) \times 10^{-3}$/cm and $(0.7 \pm 0.05) \times 10^{-3}$/cm were set in the tests.

During the course of an experiment the salinity profile is determined indirectly by measuring the conductivity profile with a conductivity probe. The probe is similar to the one developed at the Hydrodynamics Laboratory of MIT. The electrodes are 0.32 cm x 0.32 cm x 24 mil platinum plates that are 0.32 cm apart. The probe is shown schematically in Fig. 4. The conductivity probe is mounted on a traversing mechanism and the conductivity profiles are determined by measurements at 1.27 cm intervals, with the probe moving downward from the free surface. A second traverse is then made in the opposite direction. A very slight difference is observed between the two sets of measurements and the average value is used in the calculations. The conductivity probe is calibrated with salt solutions of known density; the density of the solutions is measured by an analytical balance. The densities are obtained from the calibration. The density profiles are shown in Fig. 5.

After the conductivity profiles are measured the valve of the jet fluid container is opened and the flow rate adjusted. The jet flows are driven by gravity. The fluid from the container fills a beaker so that a relatively constant head is maintained during each experiment; the overflow from the beaker is led to a drain. The discharge flow rate is measured by a flow meter which is calibrated for the jet fluid density. In order to trace the jet trajectories photographically the jet fluid is mixed with purple food color. The density of the colored jet fluid is taken as the jet fluid density.

Each jet nozzle is fabricated by connecting a 3.175 cm long .3175 cm diameter tube to a .476 cm tube. The tubes are stainless steel. A screen is attached to one end of the smaller diameter tube to insure turbulent flow at the nozzle exit. For the present investigation the jet Reynolds number ranges from 440 to 2000. The geometrical configurations of the nozzles used is shown in Fig. 6.

A Nikon F single lens reflex 35mm camera is used to trace the jet trajectories. The camera equipped with a 135mm f/2.8 telephoto lens is tripod mounted and is leveled and aligned relative to the side of the tank. Kodak Tri-x film (ASA 400) is used. Lighting is provided from above and from the front of the tank. The scale is established by photographing a grid board at a fixed and known distance. The board with a .635 cm grid machined on it is in the center frame of the jet motion. At least two pictures are taken for each run.

Measurements of jet trajectories are made directly from the photographs by using a Bishop Graphics Delux 10x optical comparator. The comparator measured up to 0.0127 cm. For each photograph measurements are made at three different locations along the trajectory and the average is considered as the appropriate value.

RESULTS AND DISCUSSION

A simplified description of the development of a buoyant jet will be helpful before presenting the experimental results.

Buoyant Jet Development

As the warm effluent discharges from the jet into a denser environment it rises due to the buoyancy force which results because of the density differences between the two fluids and, of course, the jet momentum. The nature of the environment into which a jet is discharged has a significant influence on the behavior of the jet. If the receiving water is not density stratified and the discharge is buoyant with respect to it the jet will rise to the surface and spread laterally. Regardless of the reduction of the density difference by mixing such a rise occurs because the jet is always less dense than its surroundings. However, if the receiving water density is not uniform but is stratified it is possible that the jet will not reach the surface. Because of turbulent mixing the jet entrains the denser ambient fluid and becomes heavier so that the buoyancy driving force is reduced. The jet momentum is also reduced by mixing. Since the density of the environment is decreasing with height the jet will evantually become neutrally buoyant with respect to the higher less dense ambient fluid. Because of excess vertical momentum the jet tends to overshoot this level somewhat but will settle down and spread out at a terminal level, y_t, below the surface (see Fig. 7). The location of this terminal height of rise or the level of neutral buoyancy has obvious implications with regard to waste heat disposal.

Experimental Results

The primary purpose of the present research is to obtain the terminal height of rise as a function of the discharge modified Froude number and injection angle. To verify the significance of this new dimensionless parameter each of the prime factors contained therein are independently varied. Therefore, the jet velocity is varied and the influence of the discharge location and the density of the environment on the flow characteristics are investigated independently.

Steady state results are obtained for buoyant jets discharged into stagnant linearly-stratified receiving water subject to a variety of conditions. A tabulation of all the experimentals runs is presented in Table I. Typical photographs of dye jets are shown in Figs. 8 to 9.

The effect of varying the modified Froude number on the terminal height of rise of the jet is shown in Fig. 10 for various jet inclination angles, θ. For θ = 30°, 45° and 90° the terminal height of rise increases with the Froude number. This is physically reasonable since increases in the vertical and horizontal momentum are associated with higher Froude numbers (relatively larger jet velocities). The increased vertical momentum when coupled with the vertical buoyancy force dominates the horizontal momentum. In effect the relatively large vertical forces preclude any significant mixing in the denser layers due to the horizontal momentum. For horizontal injection (θ = 0°) the terminal height of rise decreases with increasing Froude number. This is because the purely horizontal inertia force is relatively larger than the vertical buoyancy force for larger Froude numbers. As a result greater mixing occurs at the denser level and the jets become less buoyant with respect to the environment. It is also observed that for a given Froude number the terminal height of rise increases as the jet discharge angle increases.

This is because the horizontal momentum is reduced as the discharge angle increases so that there is less mixing in the denser layers.

For vertical injection ($\theta = 90°$) entrance tubes without turbulence inducing screening and sudden contractions were employed for three different modified Froude numbers. The Reynolds numbers for these runs were such that the jet entered laminarly but transitioned to turbulent after a length which decreased with increasing modified Froude number (this is equivalent to increasing Reynolds number since only the velocity was varied in the experiment). From Fig. 10 these three results for which the terminal height of rise decreases with increasing modified Froude number, contrary to the turbulent entrance results for 90° injection, reflect the effect of the inefficient mixing during the laminar portion of the jet, where the surrounding density is greatest, and the dependence of the laminar length before the transition to turbulence on the increasing modified Froude number.

To indicate the effects of mixing between the jet and its surroundings a comparison is made of the trajectories computed from Eq. (1) on the assumption of no mixing and the experimental trajectories. The latter are centerline values measured from the photographs. These results are presented in Fig. 11 for various values of $F \sin \theta$. It can be seen that for injection angles other than $\theta = 0$, or $F \sin \theta = 0$, the experimental and theoretical trajectories coincide until the mixing dissipates the kinetic energy so that the real jet is buoyancy dominated and, therefore, stops rising at the level where its density equals that of the surroundings. The mixing has a greater influence on the cases of horizontal injection $F \sin \theta = 0$. In those cases the departure of the trajectories occurs sooner. The mixing does not permit the jet to penetrate as far horizontally. The greater mixing with higher density fluid results in smaller vertical rises.

For most of the experiments the modified Froude number is varied by only changing the jet velocity. However, according to its definition, the modified Froude number can also be varied by changing the density gradient, jet fluid density, or discharge location (ρ_0). In order to verify that the modified Froude number is the significant parameter for large-scale motion of buoyant jets discharged into stratified environments additional experiments were performed at different density gradients and at different discharge levels. Three additional data points are shown in Fig. 10 for horizontal injection, $\theta = 0°$, taken for a different density gradient and three more for a different discharge location. One additional point was taken for $\theta = 45°$ for a change in density gradient and for a location change. The results can be seen in Fig. 10 to correlate well on the basis of the modified Froude number and the associated characteristic length, Y_F. This further substantiates the significance of Y_F as the proper reference length.

To complete this study an attempt was made to compare the present experimental results with any existing ones. Unfortunately, in many of the relevant papers critical data is omitted so that it was not possible to utilize those results. However, results from Refs. 3, 4, and 7 are plotted in Fig. 10. For vertical injection, $\theta = 90°$, the results of Fan and Mangarella and Van Dusen agree extremely well with present data. The only available point for discharge at $\theta = 45°$ is from Ref. 3 and it lies somewhat below the experimental line for that case. The results of Refs. 3 and 7 also agree well with the present data for horizontal injection, $\theta = 0°$. However, Fan's results are consistently lower than the present ones although both lines are essentially parallel over a large range of F. The possible reason for this discrepancy may be due to the very weak stratification in his work relative to those in the present investigation (more than two orders of magnitude lower). Since temperature variations (due to laboratory conditions or effluent heating) have a greater effect on densities at the lower stratifications the density gradient and difference might be actually have been somewhat different from the reported value. This could markedly effect the values of y/Y_F.

CONCLUSIONS

Experiments have been performed on submerged buoyant single jets that are discharged into stagnant linearly stratified environments. Measurements of the terminal height of rise of the jet were made for injection angles of 0, 30, 45, and 90°, jet entrance Reynolds numbers from 450 to 2030, and density gradients of 0.7×10^{-3}gm/cm^4 and 1.4×10^{-3}gm/cm^4. The results indicate that the terminal height of rise when scaled with the parameter $Y_F = \rho_o - \rho_j/\gamma$, correlates with the densimetric Froude number based on Y_F and the injection angle, θ. The jet trajectories for injection angles other than 0° are found to correspond closely to simple inviscid, non-mixing model up until the terminal height is attained.

The implications of these results is that it is Y_F, the distance above the jet entrance at which the density of the surrounding fluid is the same as the jet at entrance, that is the proper characteristic length for this problem and not the jet nozzle diameter which has been used heretofore.

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ACKNOWLEDGEMENT

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$\rho_j = 0.9954$ gm/ml.

Expt. No.	θ deg.	U cm/sec.	ρ gm/ml.	$\frac{1}{\rho_\ell}\frac{d\rho_a}{dy}$ ($\times 10^{-3}$/cm)	Re	F	Y_F cm	$\frac{y_t}{Y_F}$
1	0	13.84	1.0162	1.4	450	0.79	14.95	0.2052
2		20.93	1.0162	1.4	675	1.195	14.95	0.1784
3		27.84	1.0162	1.4	900	1.590	14.95	0.1627
4		34.59	1.0162	1.4	1120	1.975	14.95	0.1560
5		41.68	1.0162	1.4	1350	2.380	14.95	0.1550
6		48.59	1.0162	1.4	1570	2.775	14.95	0.1260
7		62.43	1.0162	1.4	2030	3.565	14.95	0.1161
8		20.93	1.0114	1.4	675	1.554	11.50	0.1638
9		34.59	1.0114	1.4	1120	2.568	11.50	0.1582
10		48.59	1.0114	1.4	1570	3.607	11.50	0.1251
11		20.93	1.0056	0.7	675	1.723	14.66	0.1645
12		27.84	1.0056	0.7	900	2.293	14.66	0.1732
13		34.59	1.0056	0.7	1120	2.848	14.66	0.1270
14		62.43	1.0114	1.4	2030	4.647	11.50	0.1081
15	30	20.93	1.0162	1.4	675	1.195	14.95	0.2746
16		34.59	1.0162	1.4	1120	1.975	14.95	0.2859
17		48.59	1.0162	1.4	1570	2.775	14.95	0.3085
18		62.43	1.0162	1.4	2030	3.565	14.95	0.3255
19	45	13.84	1.0162	1.4	450	0.790	14.95	0.3298
20		20.93	1.0162	1.4	675	1.195	14.95	0.3340
21		27.84	1.0162	1.4	900	1.590	14.95	0.3652
22		34.59	1.0162	1.4	1120	1.975	14.95	0.3666
23		48.59	1.0162	1.4	1570	2.775	14.95	0.3978
24		55.52	1.0162	1.4	1790	3.171	14.95	0.4133
25		62.43	1.0162	1.4	2030	3.565	14.95	0.4332
26		34.59	1.0114	1.4	1120	2.568	14.95	0.4250
27		27.84	1.0056	0.7	900	2.293	14.66	0.4157
28	90	20.93	1.0162	1.4	675	1.195	14.95	0.3652
29		27.84	1.0162	1.4	900	1.590	14.95	0.4128
30		34.59	1.0162	1.4	1120	1.975	14.95	0.4374
31		41.68	1.0162	1.4	1350	2.380	14.95	0.4746
32		48.59	1.0162	1.4	1570	2.775	14.95	0.4905
33		55.52	1.0162	1.4	1790	3.171	14.95	0.5381
34		62.43	1.0162	1.4	2030	3.565	14.95	0.5584

Table 1. Experiments on round buoyant jet into stagnant, linearly stratified enviroment

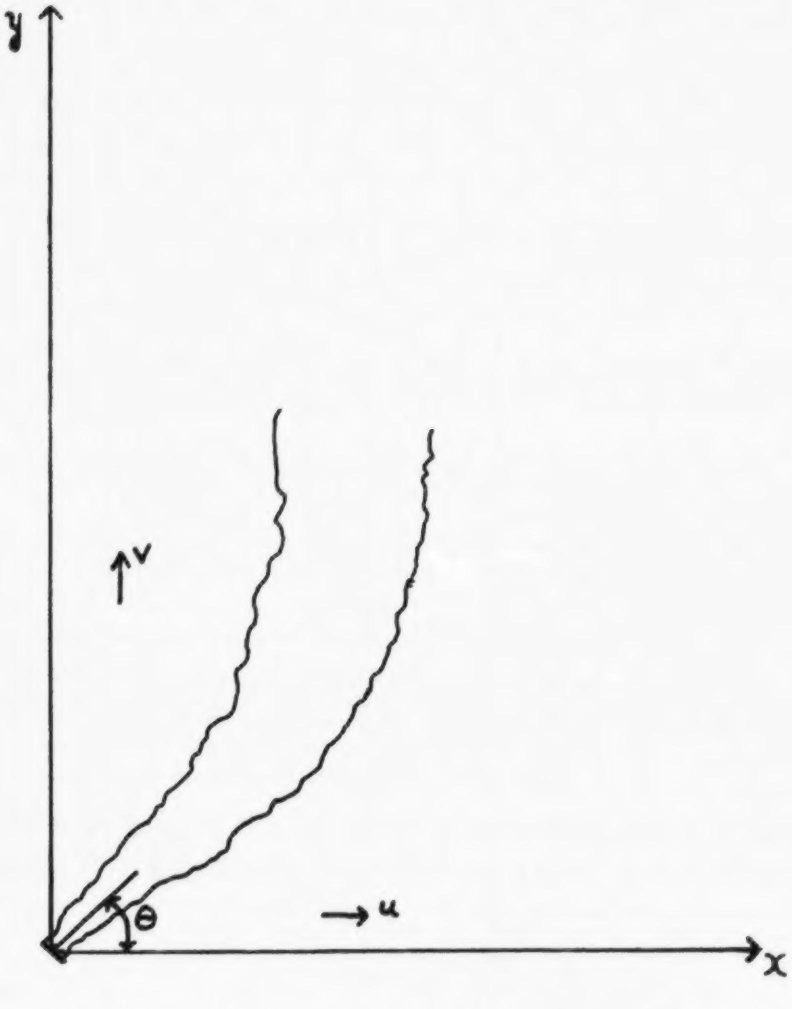


Fig. 1 The Coordinate System for the Development of the Nondimensional Parameter

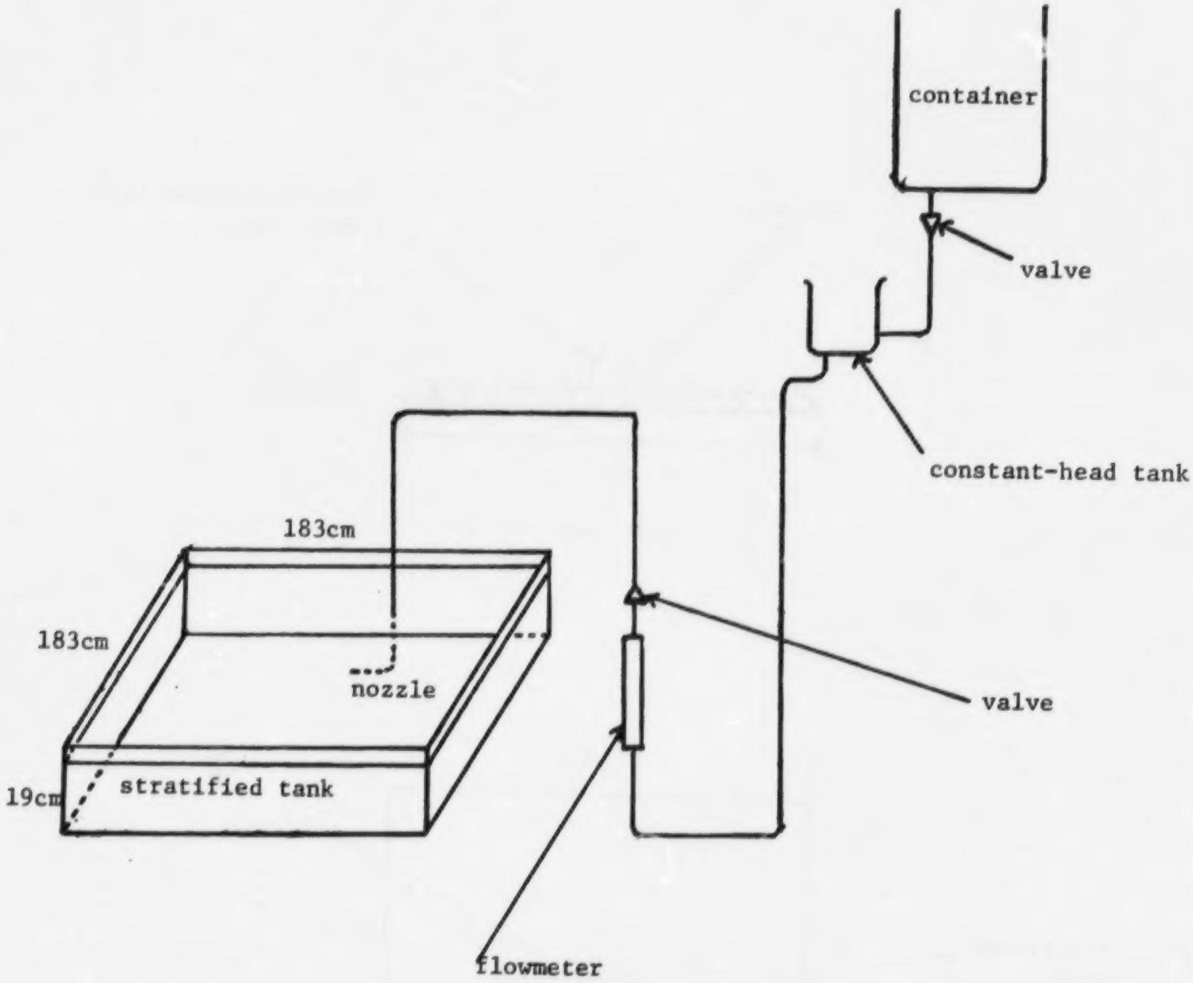
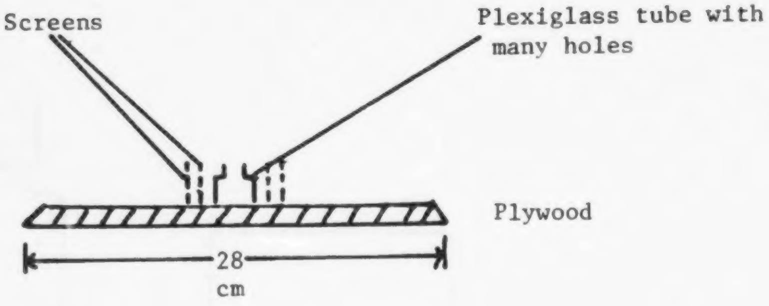
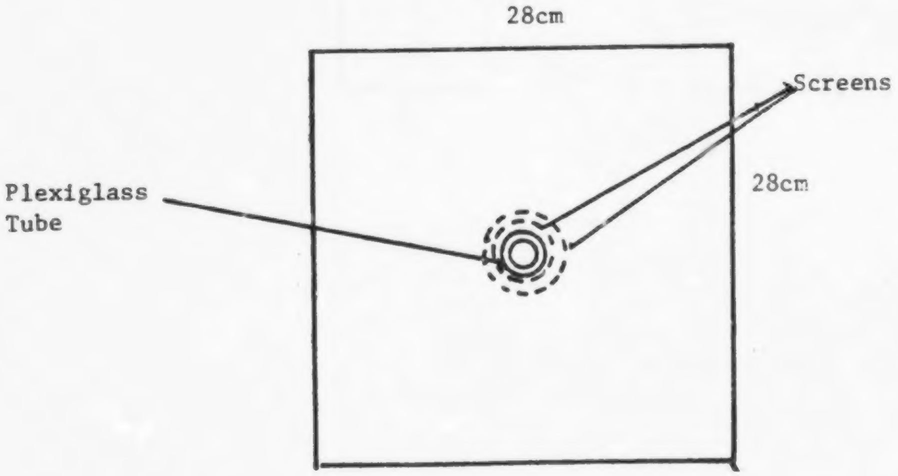

container
valve
constant-head tank
183cm
183cm
nozzle
valve
19cm
stratified tank
flowmeter

Fig. 2 Experimental Set-up


Screens
Plexiglass tube with many holes
Plywood
28 cm

Side View


28cm
Screens
28cm
Plexiglass Tube

Top View

Fig. 3 The Floating Device

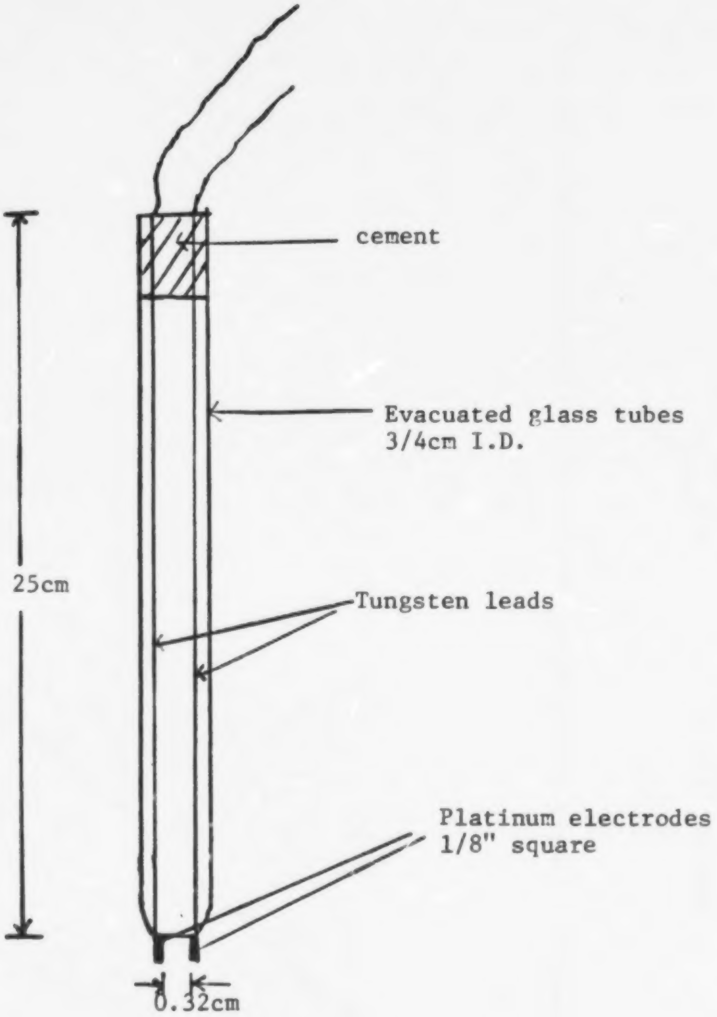

cement
Evacuated glass tubes 3/4cm I.D.
25cm
Tungsten leads
Platinum electrodes 1/8" square
0.32cm

Fig. 4 The Conductivity Probe

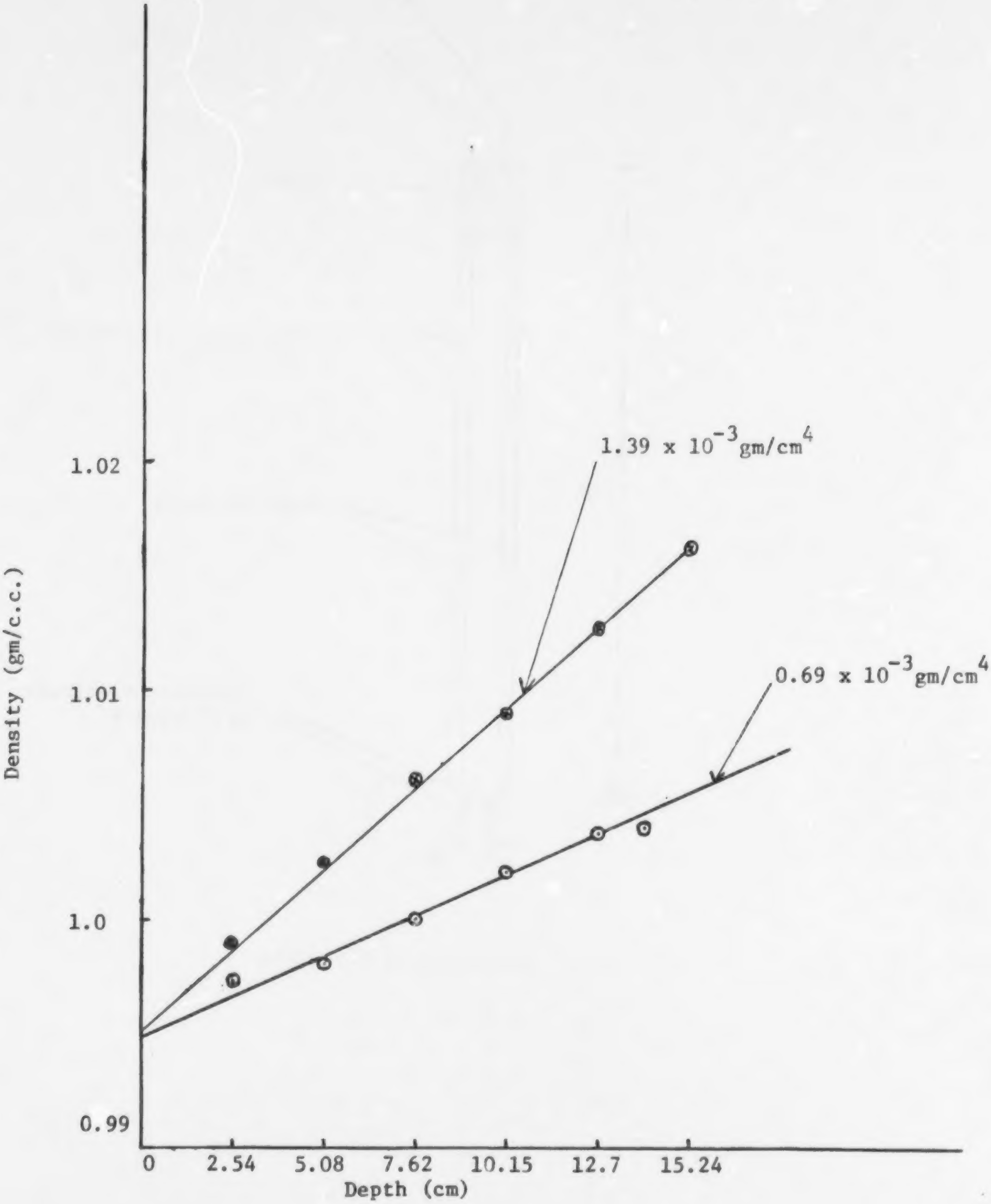
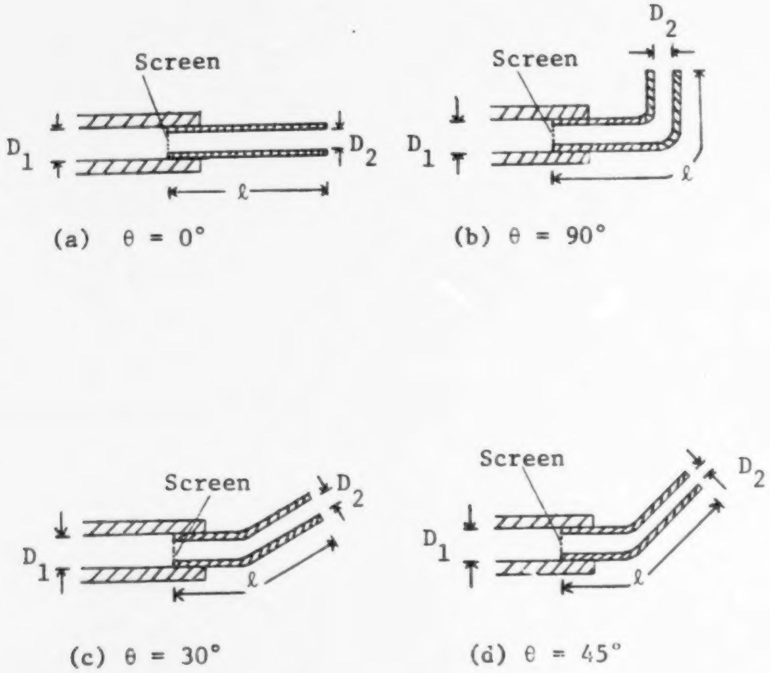


Fig. 5 Two measured Density Profiles


Screen
D_1
D_2
ℓ
Screen
D_2
D_1
ℓ
Screen
D_2
D_1
ℓ
Screen
D_2
D_1
ℓ

(a) $\theta = 0°$

(b) $\theta = 90°$

(c) $\theta = 30°$

(d) $\theta = 45°$

Nozzle	(a)	(b)	(c)	(d)
D_1(cm)	0.476	0.476	0.476	0.476
D_2(cm)	0.3175	0.3175	0.3175	0.3175
ℓ (cm)	3.175	3.175	3.175	3.175

Fig. 6 Nozzles Used in the Experiments

U = Jet exist velocity

ρ_o = Density of the environment at the jet discharge level

ρ_j = Jet fluid density

θ = Jet discharge angle

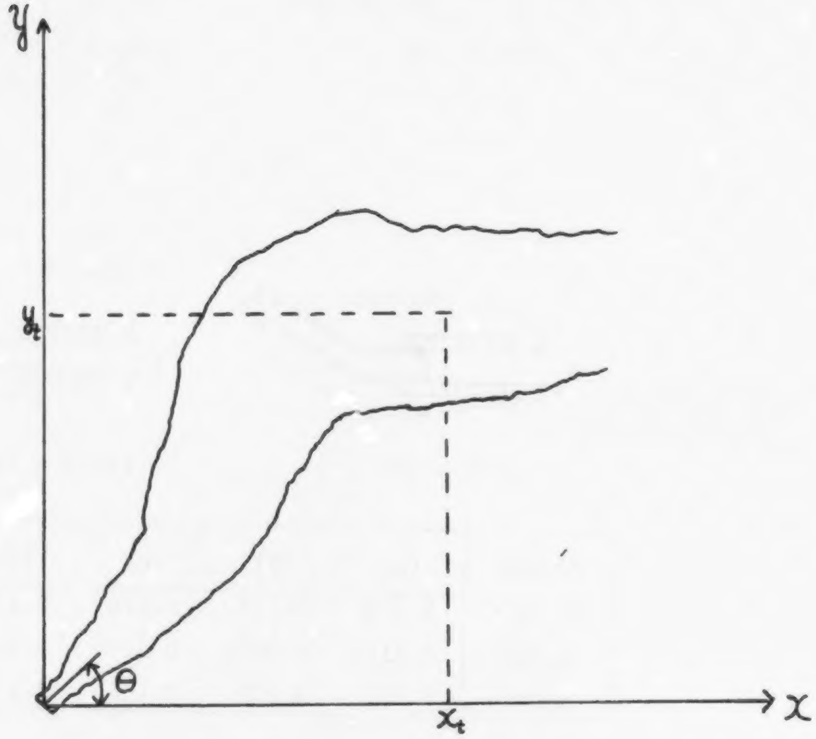


Fig. 7 Inclined Round Buoyant Jet in a Stagnant and Linearly Density-Stratified Environment

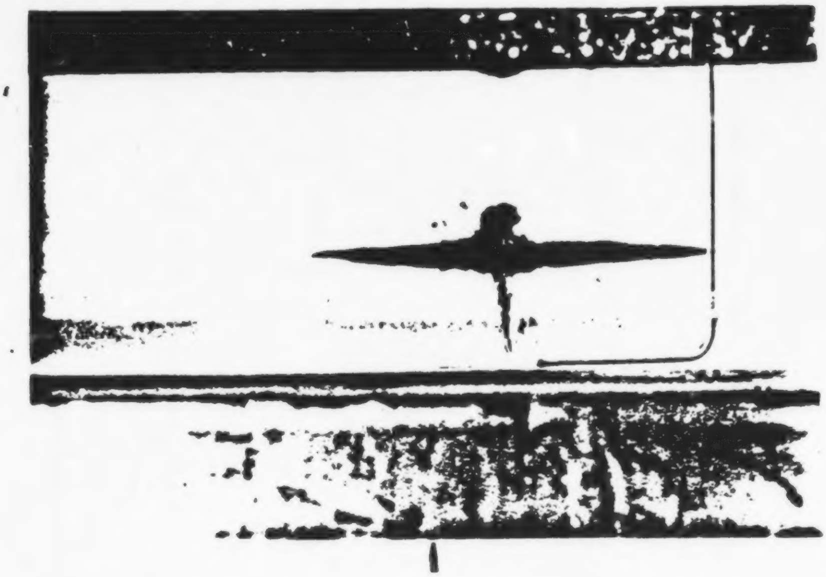


Fig. 8 Buoyant Jet in a Stangant, Linearly Stratified Environment. θ = 90°, F = 1.975,

$$\frac{1}{\rho_j}\frac{d\rho_a}{dy} = 1.4 \times 10^{-3}/\text{cm}$$

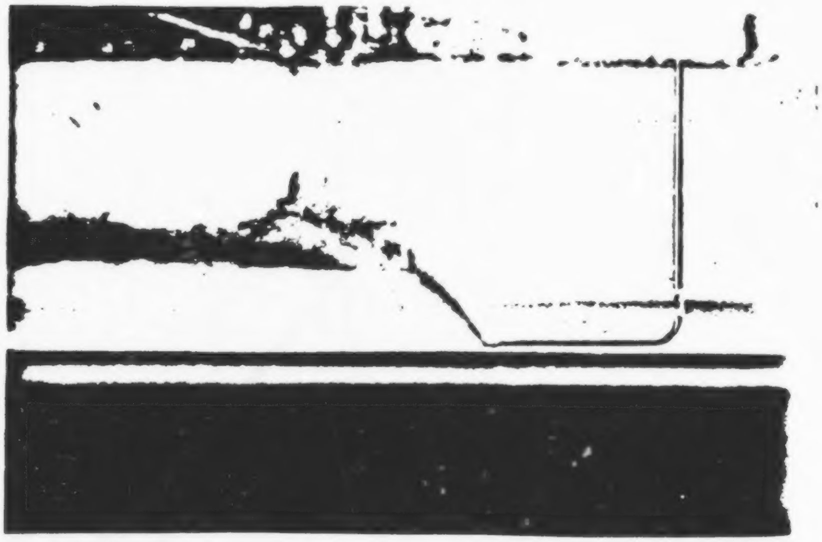
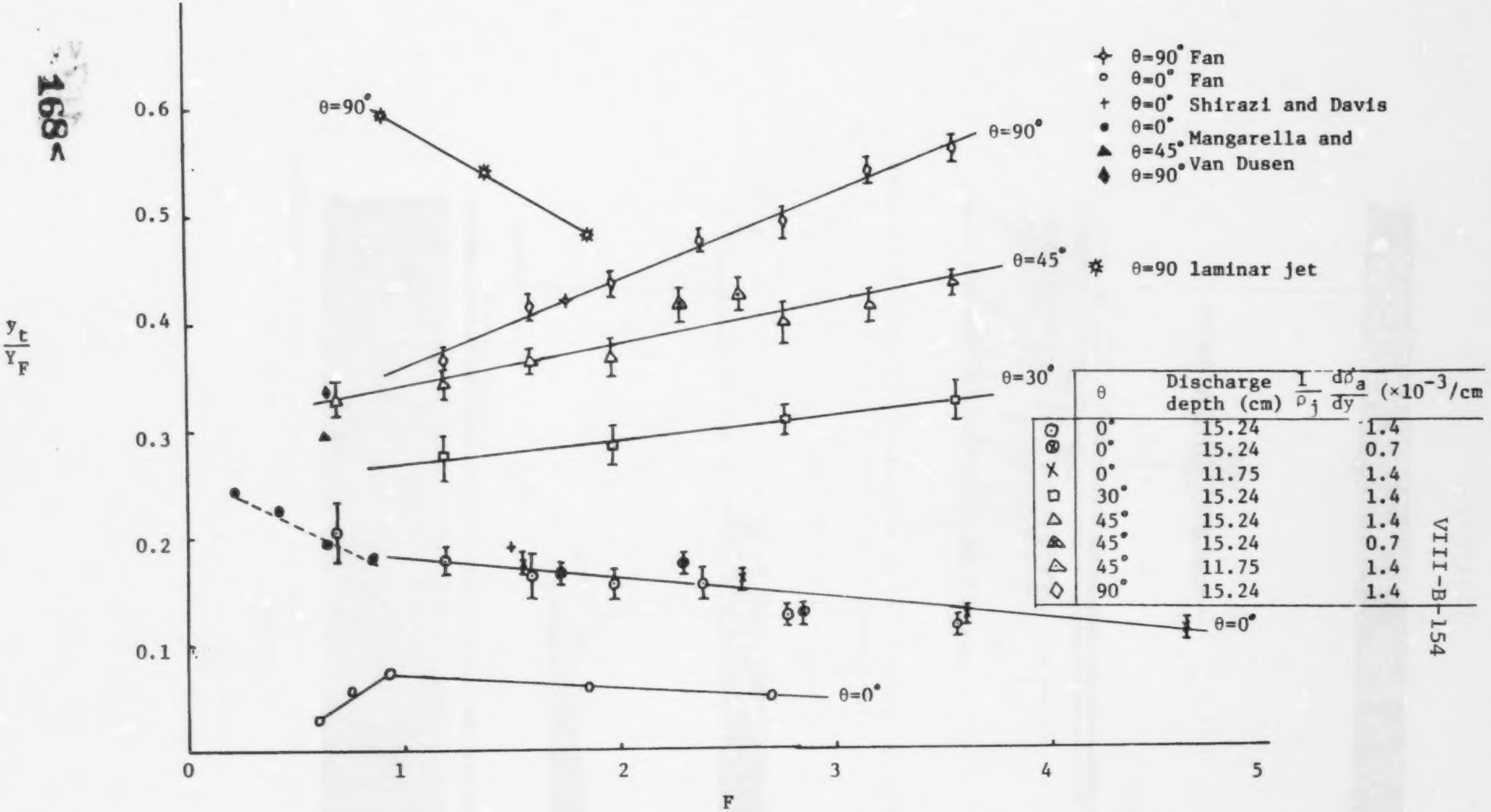


Fig. 9 Buoyant Jet in a Stagnant, Linearly Stratified Environment. θ = 45°, F = 2.775,

$$\frac{1}{\rho_j}\frac{d\rho_a}{dy} = 1.4 \times 10^{-3}/\text{cm}$$



	θ	Discharge depth (cm)	$\frac{1}{\rho_j}\frac{d\rho_a}{dy}$ (×10^{-3}/cm
⊙	0°	15.24	1.4
⊗	0°	15.24	0.7
X	0°	11.75	1.4
□	30°	15.24	1.4
△	45°	15.24	1.4
▲	45°	15.24	0.7
△	45°	11.75	1.4
◇	90°	15.24	1.4

Fig. 10 Plot of Jet Terminal Height of Rise Versus Modified Froude Number

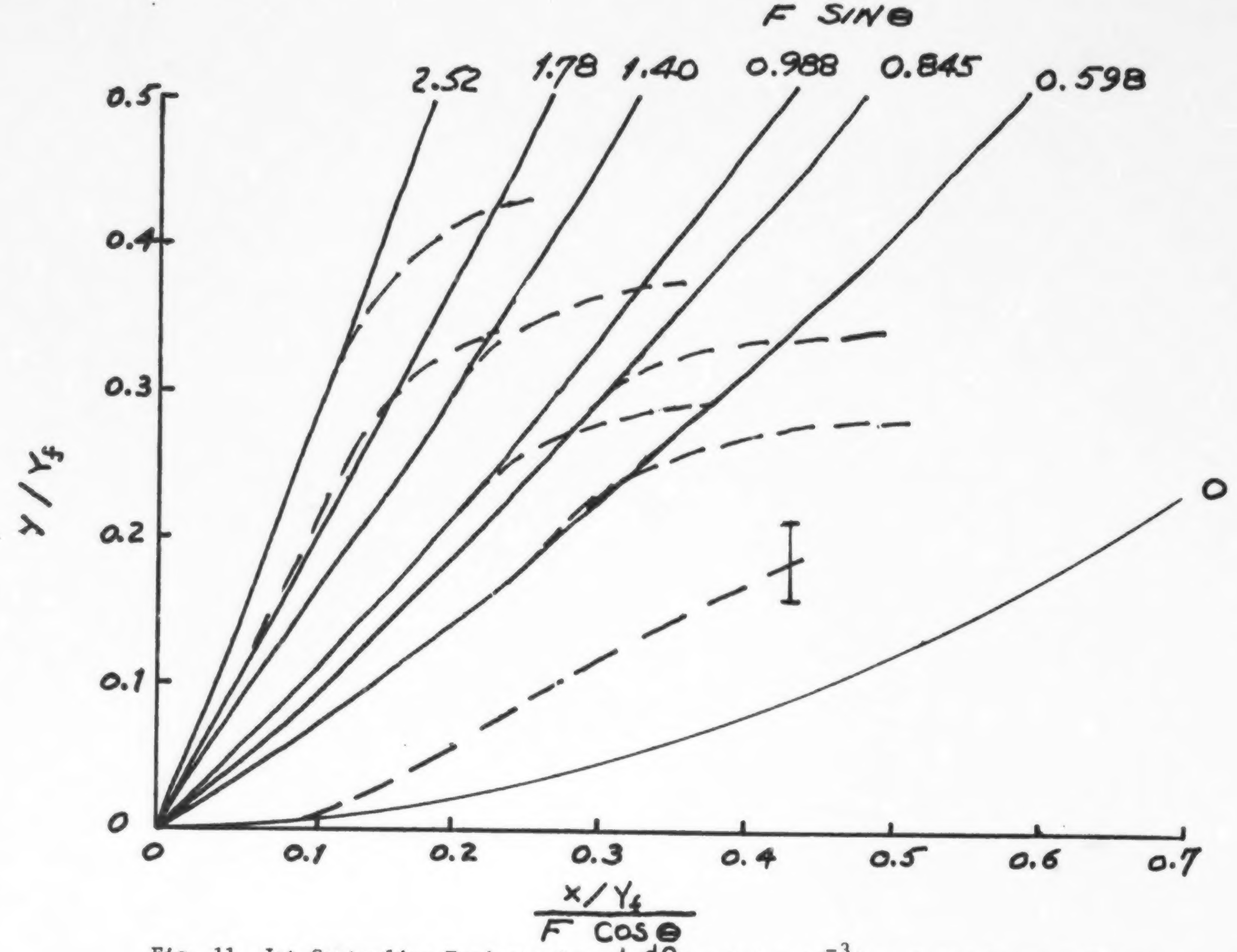


Fig. 11 Jet Centerline Trajectories, $\frac{1}{\rho_j}\frac{d\rho_a}{dy} = 1.4 \times 10^{-3}$/cm; Solid Lines - Theory; Dashed Lines - Experiment.

6-45-24

HYDRAULIC INVESTIGATIONS OF THERMAL DIFFUSION DURING HEAT TREATMENT CYCLES SAN ONOFRE NUCLEAR GENERATING STATION UNITS 2 AND 3

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California Institute of Technology
Pasadena, California U.S.A.

ABSTRACT

Hydraulic model tests were performed to determine the behavior of the ocean thermal discharge plumes from the heat treatment of Units 2 and 3 pipelines of the San Onofre Nuclear Generating Station. Heat treatment is the process of removing marine organisms growing inside a once-through condenser cooling system by occasional, temporary increases in the temperature of the discharged water. The heat treatment of both discharge and intake lines was modeled. During intake heat treatment, the roles of the discharge and intake lines are reversed.

The results of the present study show that for both intake and diffuser heat treatment the maximum distance across the heat treatment plume, as defined by the $\Delta T = 4°F$ above ambient surface isotherm, will decrease to less than 2000 ft within two hours following the end of heat treatment and the plume will not impact either the shoreline or the bottom.

INTRODUCTION

The San Onofre Nuclear Generating Station (jointly owned by the Southern California Edison Company and the San Diego Gas and Electric Company) is located on the Pacific Coast approximately halfway between Los Angeles and San Diego. Unit 1 has been in operation since 1968 at a rated output of 450 Mwe. Units 2 and 3 are now under construction and are due to begin operation in 1981 (Unit 2) and 1983 (Unit 3) at rated outputs of 1100 Mwe each.

Each unit employs its own once-through cooling system in which sea water for condenser cooling enters an intake structure located offshore, is pumped through the condenser unit and is then passed back to the ocean via an offshore discharge structure. The cooling water is warmed approximately 20°F (11.2°C) during normal operation in passage through the condenser.

The continuous passage of ocean water containing marine organisms through the cooling system results in marine growths (barnacles, etc.) on the conduits, and would, if untreated, ultimately lead to fouling of the circulating water system. The method utilized by Southern California Edison

Company to control such fouling problems is to reduce occasionally the volume rate of flow of cooling water from the ocean while recirculating a portion of the flow within the plant, thus temporarily increasing the discharge water temperature. This elevated water temperature is lethal to the attached marine fouling organisms which are consequently kept from accumulating in the circulating water system. During the period of elevated temperature the flow in the offshore conduits can also be reversed in direction, so that the intake becomes the discharge and vice versa. This results in the intake conduit also being subjected to warmer water. The entire process of elevation of the temperature of the cooling water, treatment of either the discharge or the intake conduit, and reestablishment of normal flow and temperature is called heat treatment.

In order to meet the requirements of the California state thermal discharge regulations for new discharges into coastal waters, the discharge structures of Units 2 and 3 were designed as multiport diffusers. Unit 1 was in operation before the regulations were promulgated and employs a single port discharge. Sections 3.B.(3) and (4) of these regulations read as follows:

> (3) The maximum temperature of thermal waste discharges shall not exceed the natural temperature of receiving waters by more than 20°F.
>
> (4) The discharge of elevated temperature wastes shall not result in increases in the natural water temperature exceeding 4°F at (a) the shoreline, (b) the surface of any ocean substrate, or (c) the ocean surface beyond 1,000 feet from the discharge system. The surface temperature limitation shall be maintained at least 50 percent of the duration of any complete tidal cycle.

Previous studies [1 and 2], conducted in this laboratory, showed that these regulations will not be violated during normal once-through cooling operation. During heat treatment, however, by the very nature of the process Section 3.B.(3) will be violated.

As part of the procedure for obtaining a waiver for heat treatment from the regulations, the Southern California Edison Company is sponsoring a research program to determine the most environmentally acceptable, yet effective method of heat treatment. Their biological testing program has shown that the higher the temperature used for heat treatment, the shorter is the duration required to remove the fouling organisms. The purpose of the hydraulic model studies summarized in this paper (and reported on more fully in [3]) was to predict the horizontal and vertical extent of the thermal fields in the ocean that will result from different modes of heat treatment.

TESTING PROGRAM

The purpose of the hydraulic laboratory model studies was to provide a laboratory scale representation of temperature patterns and flow fields that will occur during the various possible heat treatment cycles at San

Onofre Units 2 and 3.

The hydraulic model studies were performed by building models of the cooling water discharge and intake structures and installing them in a large shallow tank of water located in the W. M. Keck Laboratory of Hydraulics and Water Resources at the California Institute of Technology. These scaled replicas of the actual structures were then operated in the same fashion as the prototypes will be operated. The flow rates and temperatures used in the models were carefully chosen to duplicate the momentum, buoyancy and volume fluxes that will be associated with each intake and discharge in prototype operation.

The models included the intake and discharge structures of Unit 1 as well as those of Units 2 and 3. The intake heat treatment tests and diffuser heat treatment tests were conducted separately. For the intake heat treatment tests the structures were scaled at a prototype-to-model length ratio of 200:1. For the diffuser heat treatment tests distorted models were used with prototype-to-model length ratios of 100:1 vertical and 420:1 horizontal.

The layout of the prototype offshore structures at San Onofre is shown in Figure 1. The discharge structure of Unit 1 is a single oblong riser pipe ending in a large horizontal port thirteen feet below MLLW. The intake structure of Unit 1 is similar to its discharge structure, but with a velocity cap above the opening. The discharge structures of Units 2 and 3 are 2,520 ft long multiport diffusers, oriented perpendicular to shore with 63 nozzles each. The nozzles are directed offshore, 20° up from horizontal and 25° alternately on either side of the diffuser axis. The average nozzle diameter is 20.3 in., and during normal operation the average discharge velocity is 13.1 fps. The depth of the nearshore nozzle of Unit 3 diffuser is approximately 27 ft below MLLW and the depth of the offshore nozzle of Unit 2 diffuser is approximately 45 ft below MLLW. The intake structures of Units 2 and 3 are single, cylindrical risers with flanges on their lips and velocity caps positioned seven feet above the lips. The outside diameter of both the flanges and velocity caps is approximately 50 ft. The depth to the top of the velocity caps of both Units 2 and 3 intakes is approximately 12 ft below MLLW.

The most important force involved in the spreading of the heat treatment plume is that of buoyancy. This force is related to the temperature difference between the heat treatment plume and the surrounding ocean water. The surrounding ocean water is assumed to be at the natural receiving water temperature which is referred to as the ambient temperature in the rest of this paper. It is important to note that it is the temperature difference (actually, density difference) that determines the spreading and not just the discharge temperature of the heat treatment water. Therefore, all of the results presented are in terms of temperature differences. This allows for a broader use of the present results since the plume from a heat treatment discharge at one temperature into the ocean at a given ambient temperature will act the same as a plume from a discharge at a different temperature into the ocean at a different ambient temperature provided only that the temperature differences are the same. As an example, the plume from water at 125°F discharging into the ocean with an ambient temperature of 70°F will look the same as a plume from water at 110°F discharging into the ocean with an ambient temperature of 55°F. In both cases the temperature difference is 55°F. Of course, all other factors must be the same.

Throughout this paper the following symbols have been used for important temperature differences:

ΔT = temperature rise above ambient,
ΔT_o = source discharge temperature rise above ambient.

Three possible temperature levels of heat treatment were considered in the tests corresponding to heat treatment temperature increments (ΔT_o) of 70°F, 55°F and 35°F above ambient ocean temperatures. The first case of 70°F corresponds to high temperature heat treatment occurring in winter (for example, a discharge temperature of 125°F and an ambient ocean temperature of 55°F). The last case of 35°F corresponds to a low level of heat treatment occurring in summer (for example, a discharge temperature of 105°F and an ambient ocean temperature of 70°F). The $\Delta T_o = 55°F$ case could correspond to either a high level of heat treatment in the summer or a low level in the winter.

In addition to the geometry and the temperature difference between the discharged water and the ocean, the other factors which determine the extent of plume spread for various modes of heat treatment are discharge rate, duration of heat treatment and the presence of ambient ocean currents.

Assuming that the reactor continues to operate at an unchanged power level during heat treatment, the discharge rate is not an independent variable, but is related to the discharge temperature.

The durations of heat treatment that were considered were 0.5 hour, 1 hour, and 2 hour. Longer durations could not be tested due to constraints imposed by the size of the model basin.

Ambient ocean currents were considered only in the case of diffuser heat treatment, since the results of a previous test program in this laboratory [4] showed that conservative results for intake heat treatment would be given by tests with no ambient ocean current.

Only the minimum number of tests necessary to bracket the possible modes of heat treatment and their interaction with the environment were performed. These tests provide sufficient data for interpolating intermediate cases. Therefore, only the most important combinations of intake or discharge structure, temperature increment and duration of heat treatment were tested. These are summarized in Table I.

In order to obtain data on the horizontal and vertical extent of the thermal fields caused by various modes of heat treatment, three types of tests were run: (i) flow visualization, (ii) surface temperature mapping and (iii) vertical temperature profiling.

The flow visualization tests showed the source of the warm water whose temperature was measured during the temperature measuring tests. Since the other two generating units operate normally while one is being heat treated it is necessary to distinguish between the plumes. For these tests, the elevated temperature water discharging from the unit being heat treated was dyed one color and that from the normally operating units was dyed another. A 35 mm still camera mounted on the laboratory ceiling recorded the plume interactions at various times before, during and after heat treatment.

For the surface temperature mapping tests an array of thermistors (128 thermistors in the intake heat treatment tests and 112 in the diffuser heat treatment tests) was spread over the portion of the basin occupied by the heat treatment plume. Each thermistor was immersed below the surface to a depth equivalent to 1.0 to 1.5 ft in the ocean. Periodically throughout a test all thermistors in the array were sampled (within a few seconds of each other) and the data were processed by computer to yield isothermal contour plots of the nearly instantaneous surface temperatures.

The vertical temperature profiles were obtained with vertical thermistor rakes which measured the temperature at discrete depths between the surface and the bottom.

The maximum random error in the temperature measurements is estimated to have been ± 0.4°F (prototype). Complete details of the experimental techniques can be found in [3].

TEST RESULTS

Intake Heat Treatment

All of the intake heat treatment tests were performed as follows: Unit 1 was started and allowed to run alone at normal operating discharge rate and temperature for approximately one hour, prototype time. Units 2 and 3 were then started and allowed to run with Unit 1 at normal operating conditions for approximately another hour, prototype time. Heat treatment was then initiated for either Unit 2 or Unit 3 by adjusting the flow temperature and discharge and switching the direction of flow for that unit. At the end of the heat treatment time the flow was reversed again and the temperature and discharge were returned to their normal operating values. Normal operation was then continued for another hour or two, prototype time. The duration of heat treatment was measured between the emergence of the heat treatment water from the intake structure and the reversal of the flow back to normal operation.

To illustrate the type of data obtained in the intake heat treatment tests, flow visualization photographs with superimposed surface isothermal contour plots for three times during the testing of one heat treatment mode are shown in Figures 2 - 4. The heat treatment mode shown was a Unit 3 intake heat treatment with a ΔT_o of 70°F, a duration of 2.0 hr and with no ambient ocean current. It is important to bear in mind that the flow visualization test and surface temperature mapping test were run separately. There is a slight time mismatch.

The results of the flow visualization tests are presented here in the form of black and white prints reproduced from the slides taken by the overhead camera. In the original color slides, water discharged by normally operating units appeared blue while that discharged by units undergoing heat treatment appeared red. In order to distinguish the heat treatment plume in the black and white prints, all water appearing red in the slides has been shaded in with small dots in the prints. It must be emphasized that these photographs only indicate the areal extent of water from a given source and do not indicate the temperatures of the plumes. Dye intensity and temperature are not directly related.

All of the information given in the superimposed isothermal plots is in terms of prototype values. The border with scale marks corresponds to the border of the thermistor array in the test basin. The scale marks correspond to 500 foot intervals and the offshore direction is toward the top of the page. Across the top of each plot is given the test series designation, the time of the temperature measurement relative to the start of heat treatment and the duration of heat treatment in the test. The letters scattered about the plots correspond to local maxima and minima in the temperature field, the values of which, in °F above the ambient ocean temperature, are given to the right of the plots under "LEGEND". The contours plotted correspond to surface isotherms of 1°F, 2°F, 4°F, 6°F, 10°F, 15°F, 20°F... above ambient. Where possible, the isotherms have been labeled with their value in °F above ambient and the 4°F above ambient isotherm has been thickened. In the plots, Unit 3 diffuser appears as a straight line, the intake structures of Units 2 and 3 appear as octagons, and Unit 1 intake and discharge appear as squares. Unit 1 discharge is in the lower right-hand corner. Unit 3 diffuser can be seen extending beyond the boundary of the thermistor array as a row of small dots. Unit 2 diffuser is beyond the edge of the figure.

The entire test basin is not shown in the figures. In all intake heat treatment tests, in terms of prototype distances, the basin walls were located at 2,300 ft inshore, 4,500 ft offshore, 2,200 ft upcoast (to the right) and 1,800 ft downcoast (to the left) of the Unit 3 intake.

Figure 2 shows the normal operation of all three units just prior to heat treatment. Unit 1 had been in operation for approximately two hours and Units 2 and 3 for approximately one hour. The waviness in the diffuser plume could be a transient phenomenon related to the start-up of the diffuser, since it appears to decrease with time. In all of the tests, the highest temperature increment observed in the Unit 3 diffuser plume, uninfluenced by heat treatment water, was below 3°F. The tendency of the plume from Unit 1 discharge to move towards Unit 2 intake should also be noted. This was observed repeatedly in the experiments and is probably due to the flow field induced by Unit 3 diffuser as well as Units 2 and 3 intakes.

Figure 3 shows the flow field just at the end of the two hour heat treatment. Since the Unit 3 intake is being heat treated, Unit 3 diffuser is acting as an intake and therefore is producing no plume.

Figure 4 shows the flow field approximately one hour after the end of heat treatment (3.1 hr after the start of heat treatment). Unit 3 diffuser is again discharging water and the resultant surface current is drawing both the plume from Unit 1 and the decaying heat treatment plume towards the diffuser and offshore. The 1°F and 2°F ΔT isotherms in the upper right and left corners are from the "bounce back" of the diffuser plumes from the end of the basin and is the reason the tests could not continue beyond two hours after the end of heat treatment.

Comparing Figures 3 and 4 it can be seen that even though the total plume spread is greater one hour after the end of heat treatment, the average plume surface temperature is lower and the extent of the 4°F above ambient isotherm has actually decreased.

Figure 5 shows the results of the surface temperature mapping test of a Unit 2 intake heat treatment with a 2.0 hr duration at $\Delta T_o = 70°F$. Again, there was no ambient ocean current. The plot is similar to that used to show Unit 3 intake heat treatment in Figures 2 - 4, but this time fewer temperature contour intervals have been used (1°F, 4°F, 10°F, 20°F, 30°F... above ambient) and the isotherms for two different times have been drawn on the same plot. The two times are (i) at the end of heat treatment and (ii) one hour after the end of heat treatment. Since Unit 2 is being heat treated, Unit 3 diffuser and intake are operating normally throughout the test and, as shown by Figure 5, cause the heat treatment plume from Unit 2 intake to drift towards Unit 3. Therefore, the area enclosed by the 4°F above ambient isotherm, due to heat treatment, can be decreasing while the maximum distance of the isotherm from its source structure can still be increasing.

Although no vertical temperature profiles will be presented in this paper (they are presented in [3]), the general result of the vertical temperature profiling tests was that, at zero ocean current, the warm heat treatment water formed a well-defined surface layer approximately 10 ft thick within 50 ft of the intake structure. With increasing distance from its point of origin and increasing time after the end of heat treatment the surface temperature decreased and the vertical extent of the layer increased (to about 20 ft).

The major results of all the intake heat treatment tests are summarized in Table II.

The depth temperature measurements show that the plume is well stratified and should not touch bottom or cause recirculation problems for the units operating in their normal mode.

The surface temperature measurements show that:

(1) For each heat treatment test the plume (measured by the $\Delta T = 4^\circ F$ isotherm) reaches its maximum areal extent shortly after the end of heat treatment and then begins to decrease. At no time during any of the tests did the plume surface area exceed that of a circle with a 1,000 ft radius (72 acres).

(2) For shorter durations and equal ΔT_o the plume extent is slightly less, but for equal duration and smaller ΔT_o the plume extent is about the same.

(3) The current due to the discharge from the Unit 3 diffuser draws the heat treatment plumes offshore and causes the Unit 2 heat treatment plume to drift towards Unit 3 thereby increasing the distance between the intake and the $\Delta T = 4^\circ F$ isotherm.

(4) The maximum distance across the area enclosed by the $\Delta T = 4^\circ F$ isotherm decreases to less than 2,000 ft by 2.0 hr after the end of heat treatment.

Diffuser Heat Treatment

All of the diffuser heat treatment tests were performed as follows: all three units were started and allowed to run at normal operating discharge and temperature for approximately one and a half hours, prototype time. Heat treatment was then initiated for the Unit 3 diffuser by adjusting the temperature and discharge to their heat treatment values. Near the end of the heat treatment time the temperature and discharge were returned to their normal operating values. Normal operation was then continued for another few hours, prototype time. The duration of heat treatment was measured between the emergence of heat treatment temperature water from the furthest offshore nozzle of the diffuser and the beginning of the temperature change back to normal operating temperature at the same nozzle at the end of heat treatment.

To illustrate the type of data obtained in the diffuser heat treatment tests, surface isothermal contour plots for two different times during tests of two different modes of heat treatment are shown in Figures 6 - 9. The format of the surface temperature isotherm plots is similar to that used in the previous section. The test series designation, time the measurement was taken (relative to the beginning of heat treatment) and duration of heat treatment are given across the top. The grid marks are at 1,000 ft intervals, and the border indicates the extent of thermistor coverage. The diffusers appear as straight lines in the plots while the intakes of Units 2 and 3 appear as octagons and the intake of Unit 1 appears as a square just on the edge of the plot. Unit 1 discharge is located off the plot just below Unit 1 intake. The positions of local maximum and minimum temperatures are shown by letters on the plot and their values relative to ambient in °F, prototype, are given at the right under "LEGEND". The contour lines correspond to measured isotherms of 1°F, 2°F, 4°F and 6°F above ambient, as labeled. In terms of prototype distances, the basin walls were located 1,750 ft inshore, 6,650 ft offshore, 6,150 ft downcoast (to the left) and 8,150 ft upcoast (to the right) of the Unit 3 intake structure.

Figures 6 and 7 show the surface isothermal patterns near the end of heat treatment and about 2.6 hrs after the end of heat treatment, respectively, for a 2.0 hr duration heat treatment of Unit 3 diffuser at a ΔT_o of 70°F. There is no ambient ocean current present. As in the previously described intake heat treatment tests, the plume from Unit 1 is drawn towards the Unit 3 diffuser. Of special interest are the generally low temperatures of the plumes, even during heat treatment, and the disappearance of the ΔT = 4°F isotherm by 2.6 hrs after heat treatment.

Figures 8 and 9 show the thermal field at the end of heat treatment and 4.5 hrs after the end of heat treatment, respectively, for a 2.0 hrs duration heat treatment of Unit 3 diffusers at a ΔT_o of 70°F. In this test there was a steady 0.3 knot ambient ocean current from left to right (upcoast). Of interest is the small area enclosed by the ΔT = 4°F isotherm. By 4.5 hrs after the end of heat treatment all heat treatment plume water had decreased to less than 3°F above ambient and had been carried beyond the thermistor array area. Therefore, the thermal field in Figure 9 is what might be expected from normal operation of all three units (except for the influence of the offshore wall at the top of the figure).

The vertical temperature measurements showed that the heat treatment plumes were fairly well mixed vertically at a position 500 ft upcoast (to the right) of Unit 3 diffuser when an ambient ocean cross current was present. For the test shown in Figures 6 and 7, however, where no cross current was present, the vertical temperature measurements showed a well stratified heat treatment plume. In this case (with ΔT_o = 70°F) the diffuser jets may not have been turbulent. If so, the results may not be accurate, but will be conservative (give an upper limit for the plume spread).

The major results of the diffuser heat treatment tests are summarized in Table III. Even for the most severe cases tested (2.0 hr duration at ΔT_o = 70°F) no water with a ΔT greater than 4°F was found to impinge on the bottom at any time or be present on the surface after 2.6 hrs following the end of heat treatment.

CONCLUSIONS

The purpose of the hydraulic model study summarized in this paper was to predict the extent of the thermal fields in the ocean that will result from different modes of heat treatment of the circulating water system pipelines of the San Onofre Nuclear Generating Station Units 2 and 3. The study was necessary because, by its very nature, heat treatment could not meet Section 3.B.(3) ($\Delta T_o \leq 20°F$) of the California state thermal discharge regulations (California State Thermal Plan).

Although Section 3.B.(3) will be violated, the present study has shown that there is a high probability no other sections of the California State Thermal Plan will be violated. The present investigation has shown that there is very little chance of the heat treatment plumes from San Onofre Units 2 and 3 impacting either the shoreline or the bottom. The investigation has also shown that, for all cases of heat treatment of two hour duration or less, the maximum size of the area enclosed by the 4°F above ambient isotherm at no time exceeds the size of the area enclosed by a line drawn around the structure at a distance of 1,000 ft from it. This, however, does not necessarily meet the letter of the state thermal plan since at certain times and in certain directions the location of the 4°F above ambient isotherm from a heat treatment plume is more than 1,000 ft away from the structure where the plume originated. The size of the enclosed area may be less than that implied by the state thermal plan while the plume position is not, because the plume can drift and deform in the currents set up by the diffusers, especially after the end of heat treatment. It is possible the letter of Section 3.B.(4) of the thermal plan may still be met, however, because the extent of the 4°F above ambient isotherm decreases with time soon after the end of heat treatment. This is primarily due to interfacial mixing with the cooler water below the plume. One half of a complete tidal cycle is slightly longer than six hours. For intake heat treatment, the longest time that the present tests could be run was four hours after the beginning of heat treatment. The test which resulted in the $\Delta T = 4°F$ isotherm, due to heat treatment, being farthest away from its source at the end of the test period, was for a Unit 2 intake heat treatment of two hours duration at a ΔT_o of 70°F. In this test, the $\Delta T = 4°F$ above ambient surface isotherm was approximately 1300 ft away from the intake at its farthest point and was shrinking toward the intake. Within the next two hours it could well shrink to less than 1000 ft from the intake. Therefore, the heat treatment of San Onofre Units 2 and 3 as modeled in the present test may, in fact, meet all of the California State Thermal Plan except Section 3.B.(3).

In addition to meeting the letter of the California State Thermal Plan (except Section 3.B.(3)), the results of the present investigation may help to determine the least environmentally harmful mode of heat treatment by showing differences in the discharge plumes between higher temperature heat treatments of shorter duration and lower temperature ones of longer duration (e.g., 1.0 hr duration at $\Delta T_o = 70°F$ and 2.0 hr duration at $\Delta T_o = 55°F$). The intake heat treatment tests show that the plume's maximum extent is less for the shorter duration heat treatment, while the plume's decay rate is about the same in both cases. Therefore, for the shorter duration intake heat treatment less ocean surface would be affected for a shorter time. In addition, a shorter duration (with more in plant recirculation) means that there would be less "entrainment" of biota into the cooling system during heat treatment (although they would be exposed to a higher temperature and possibly recirculated within the plant more) than in the longer duration heat treatment case. For diffuser heat treatment, the tests show that the plume's area will probably be larger for the higher temperature case, but that the plume will be present for a shorter time than in the longer duration, lower temperature case. Even in the high temperature case ($\Delta T_o = 70°F$), however, the plume will be fairly cool with only a very small area over 6°F above ambient. Therefore, in both intake and diffuser heat treatment the shorter duration modes will probably be preferable.

ACKNOWLEDGMENTS

Primary support for this project came from a contract from the Southern California Edison Company to the W. M. Keck Laboratory of Hydraulics and Water Resources. Partial support for the preparation of this paper came from discretionary funds of the Environmental Quality Laboratory, California Institute of Technology.

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Table I. PROTOTYPE CONFIGURATIONS FOR LABORATORY TESTS.

T and Q refer to temperature and discharge rate.
Subscripts 1,2,3 refer to Units 1,2,3 and a refers to ambient.

Test Series	Basin Orientation	Scale	Dis-tortion Factor	Current Velocity (knots)	Q_1 (cfs)	T_1 (^oF)	Q_2 (cfs)	T_2 (^oF)	Q_3 (cfs)	T_3 (^oF)	T_a (^oF)
A1(set+of 7)	Long	200:1	1	0	700	75	530*	125*	1850	75	55
A2(set of 2)	Long	200:1	1	0	700	75	675*	110*	1850	75	55
A3(set of 3)	Long	200:1	1	0	700	90	1055*	105*	1850	90	70
A4(set of 4)	Long	200:1	1	0	700	75	1850	75	530*	125*	55
B1(set of 3)	Short	100:1	4.20	0.3	700	75	1850	75	530**	125**	55
B2(set of 3)	Short	100:1	4.20	0.3	700	90	1850	90	1055**	105**	70
B3(set of 2)	Short	100:1	4.20	0	700	75	1850	75	530**	125**	55

*Intake heat treatment
**Diffuser heat treatment
+Sets differ because of variation in duration of prototype heat treatments chosen and because of the necessity to perform various tests (such as flow visualization, surface temperature mapping, or vertical temperature profiling).

Table II. SUMMARY OF TEST RESULTS - PLUME TEMPERATURE AND EXTENT SONGS UNITS 2 AND 3 INTAKE HEAT TREATMENT.

Test Description	Unit 3 Heat Treatment 2.0 hr Duration $\Delta T_o = 70^{\circ}F$ No Ocean Current	Unit 2 Heat Treatment 2.0 hr Duration $\Delta T_o = 70^{\circ}F$ No Ocean Current	Unit 2 Heat Treatment 1.0 hr Duration $\Delta T_o = 70^{\circ}F$ No Ocean Current	Unit 2 Heat Treatment 0.5 hr Duration $\Delta T_o = 70^{\circ}F$ No Ocean Current	Unit 2 Heat Treatment 2.0 hr Duration $\Delta T_o = 55^{\circ}F$ No Ocean Current	Unit 2 Heat Treatment 2.0 hr Duration $\Delta T_o = 35^{\circ}F$ No Ocean Current
Maximum Measured Depth of $\Delta T = 4^{\circ}F$ Isotherm in H.T. Plume	12 ft	13 ft	12 ft	--	--	18 ft
Depth of $\Delta T = 4^{\circ}F$ [1] Isotherm in H.T. Plume at Distance of Normally Operating Intake	11 ft	9 ft	8 ft	--	--	10 ft
Time of Last [2] Plot During H.T.	2.0 hr	2.0 hr	1.0 hr	0.5 hr	1.6 hr	2.0 hr
Time of Maximum [2] Measured H.T. Plume Area	2.5 hr	2.6 hr	1.2 hr	0.7 hr	2.1 hr	2.0 hr
Time of End of [2] H.T. Test	3.1 hr	3.7 hr	2.8 hr	2.1 hr	3.9 hr	4.0 hr
Surface Area [3] of 4°F ΔT from H.T. (in acres)	62 68 59	62 64 44	53 59 18	39 50 12	62 66 17	67 67 6
Maximum Distance from Source to 4°F ΔT from H.T. (ft)	1060' 1120' 1140'	1240' 1280' 1260'	1020' 1100' 980'	860' 980' 900'	1080' 1120' 900'	1160' 1160' 980'
Maximum Measured [4] Surface ΔT from H.T.	43°F 12°F 9°F	30°F 16°F 8°F	27°F 12°F 5°F	31°F 12°F 5°F	23°F 12°F 5°F	14°F 14°F 4°F

[1] In Unit 2 tests this is ≈ 50 ft from Unit 3 intake. In Unit 3 test this is ≈ 500 ft from Unit 3 intake but on opposite side from Unit 2 intake.

[2] All times are relative to start of heat treatment.

[3] Errors: +5 acres from interference of Unit 1 discharge plume (when in question, attributed to heat treatment. See flow visualization pictures for interpretation).
±3 acres from estimation of location of isotherms falling outside measurement area.

[4] In Unit 3 heat treatment tests the temperature measurement probe was located closer to discharging intake than in Unit 2 tests.

Table III. SUMMARY OF TEST RESULTS - PLUME TEMPERATURE AND EXTENT SONGS UNITS 2 AND 3 DIFFUSER HEAT TREATMENT.

Test Description	Unit 3 Heat Treatment 2.0 hr Duration $\Delta T_o = 70^oF$ 0.3 knot Ocean Current			Unit 3 Heat Treatment 2.0 hr Duration $\Delta T_o = 35^oF$ 0.3 knot Ocean Current			Unit 3 Heat Treatment 2.0 hr Duration $\Delta T_o = 70^oF$ No Ocean Current		
Maximum Measured Depth of $\Delta T=4^oF$ Isotherm in H.T. Plume		0			0			0 ft	
Maximum Measured Depth of $\Delta T=2.5^oF$ Isotherm in H.T. Plume		8 ft			0			5 ft	
Time of Last Plot [1] During H.T.	2.0 hr			2.0 hr			1.9 hr		
Time of Max. Measured [1] H.T. Plume Area		2.0 hr			--			2.2 hr	
Time of Last Usable [1] Data from H.T. Test			4.0 hr			3.9 hr			4.6 hr
Surface Area of $4^o \Delta T$ from H.T. (in acres)	9	9	0	0	0	0	96	110	0
Maximum Distance from Source to 4^oF ΔT from H.T. (ft)	590'	590'	0	0	0	0	1550'	1590'	0
Maximum Measured Surface ΔT from H.T.	4^oF	4^oF	3^oF	2^oF	--	1^oF	6^oF	6^oF	3^oF

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[1] All times are relative to start of heat treatment.

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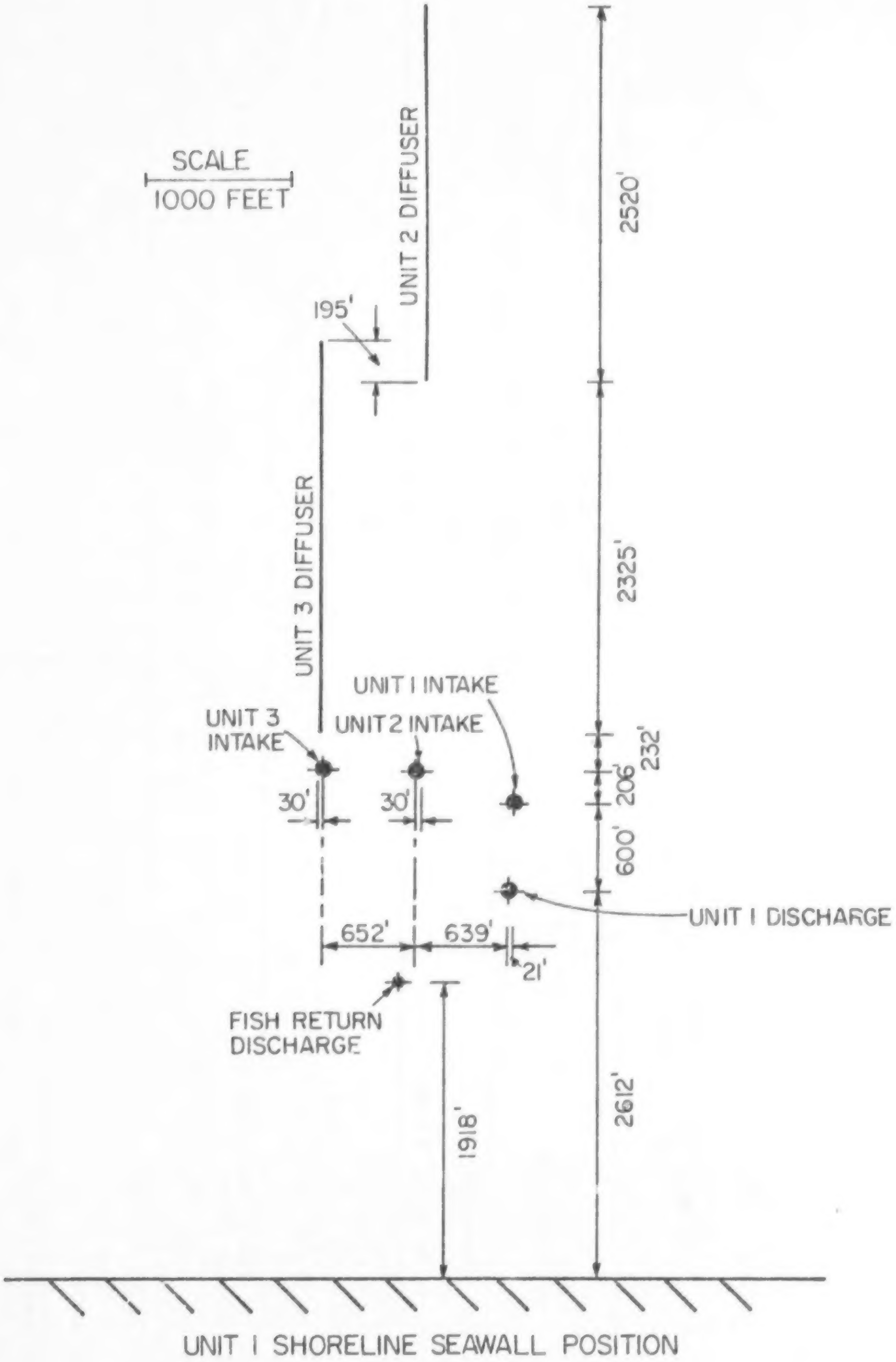
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195'
2520'
UNIT 3 DIFFUSER
2325'
UNIT 1 INTAKE
UNIT 3 INTAKE
UNIT 2 INTAKE
232'
206'
30'
30'
600'
UNIT 1 DISCHARGE
652'
639'
21'
FISH RETURN DISCHARGE
1918'
2612'
UNIT 1 SHORELINE SEAWALL POSITION

Figure 1. Physical layout of offshore structures at San Onofre.

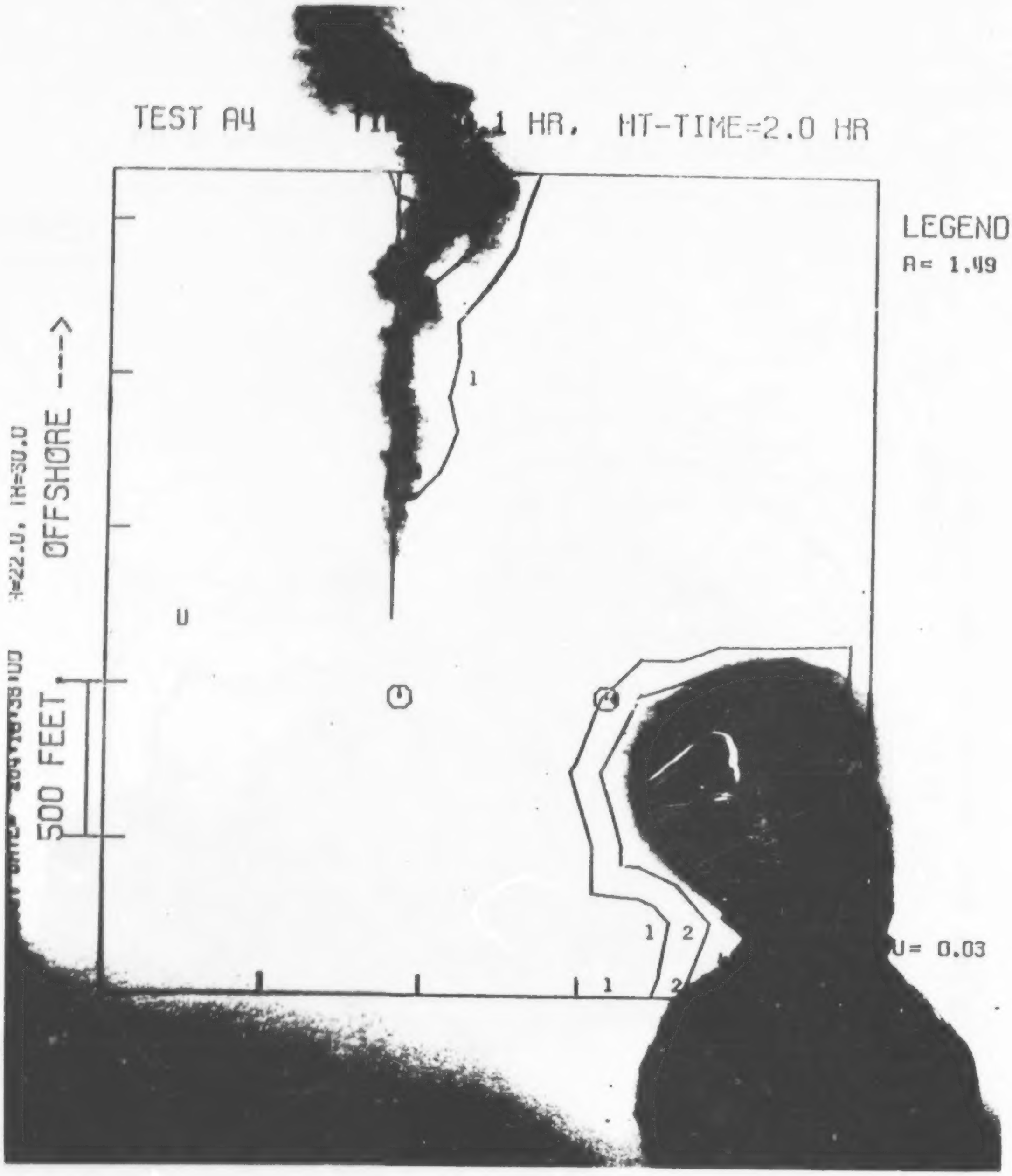

Figure 2. Surface isothermal contour plot superimposed on flow visualization photograph of normal operation of all units just prior to heat treatment with no ambient current. All temperatures are in °F above ambient. $\Delta T_o = 20°F$.

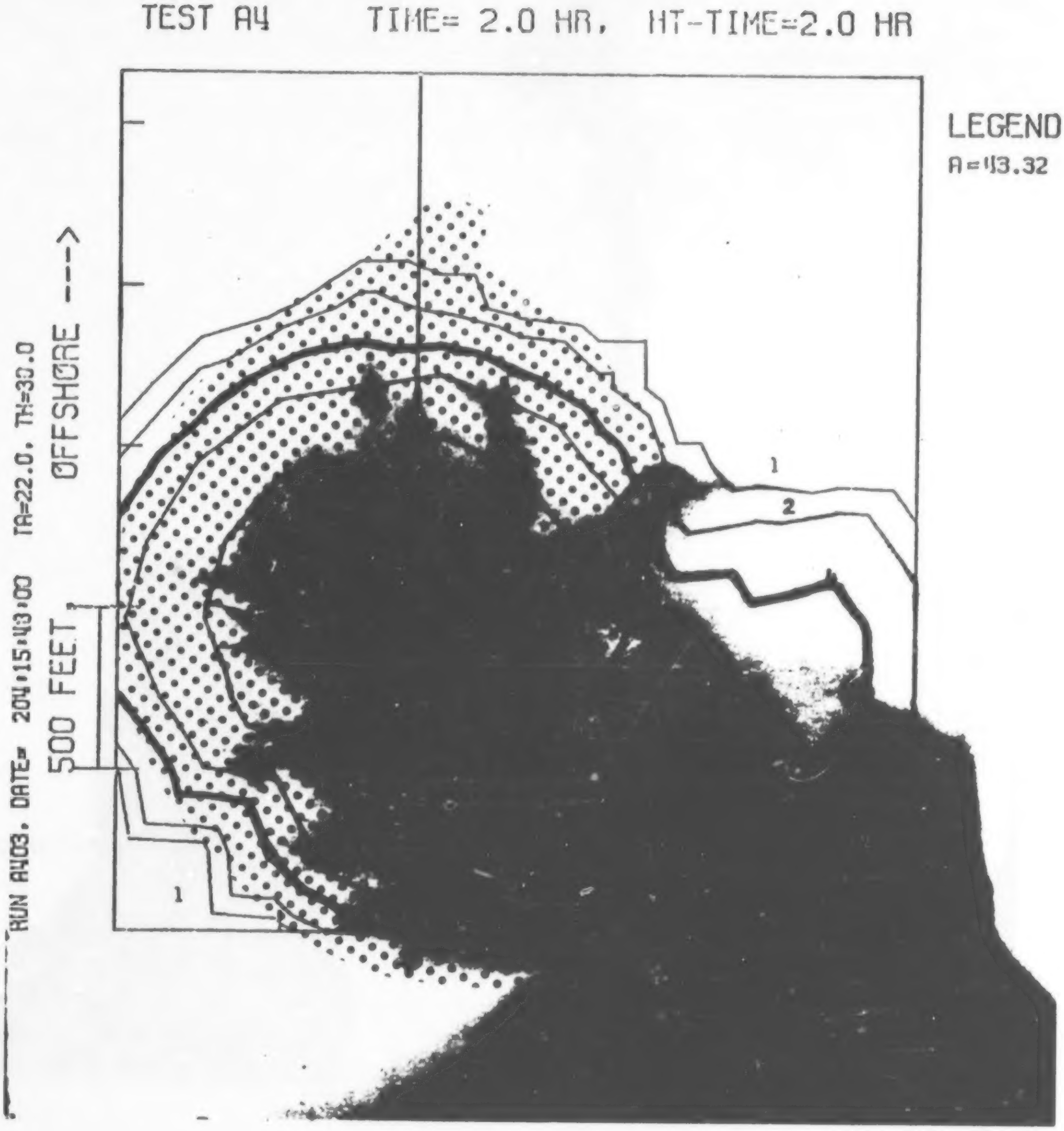

Figure 3. Surface isothermal contour plot superimposed on flow visualization photograph of Unit 3 intake heat treatment of 2.0 hour duration with $\Delta T_0 = 70°F$ and no ambient current. Time of plot: end of heat treatment. All temperatures are in °F above ambient.

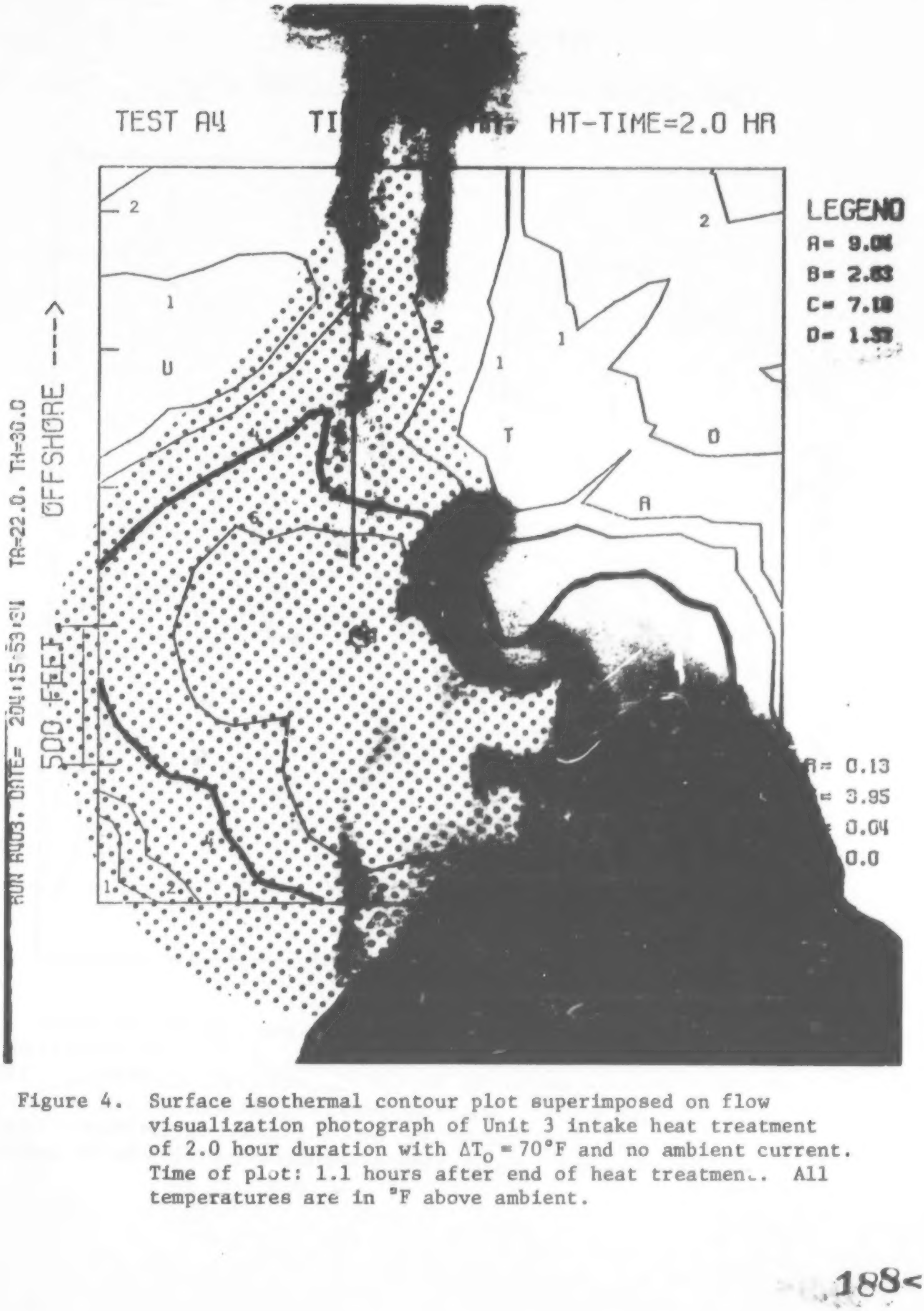

Figure 4. Surface isothermal contour plot superimposed on flow visualization photograph of Unit 3 intake heat treatment of 2.0 hour duration with $\Delta T_0 = 70°F$ and no ambient current. Time of plot: 1.1 hours after end of heat treatment. All temperatures are in °F above ambient.

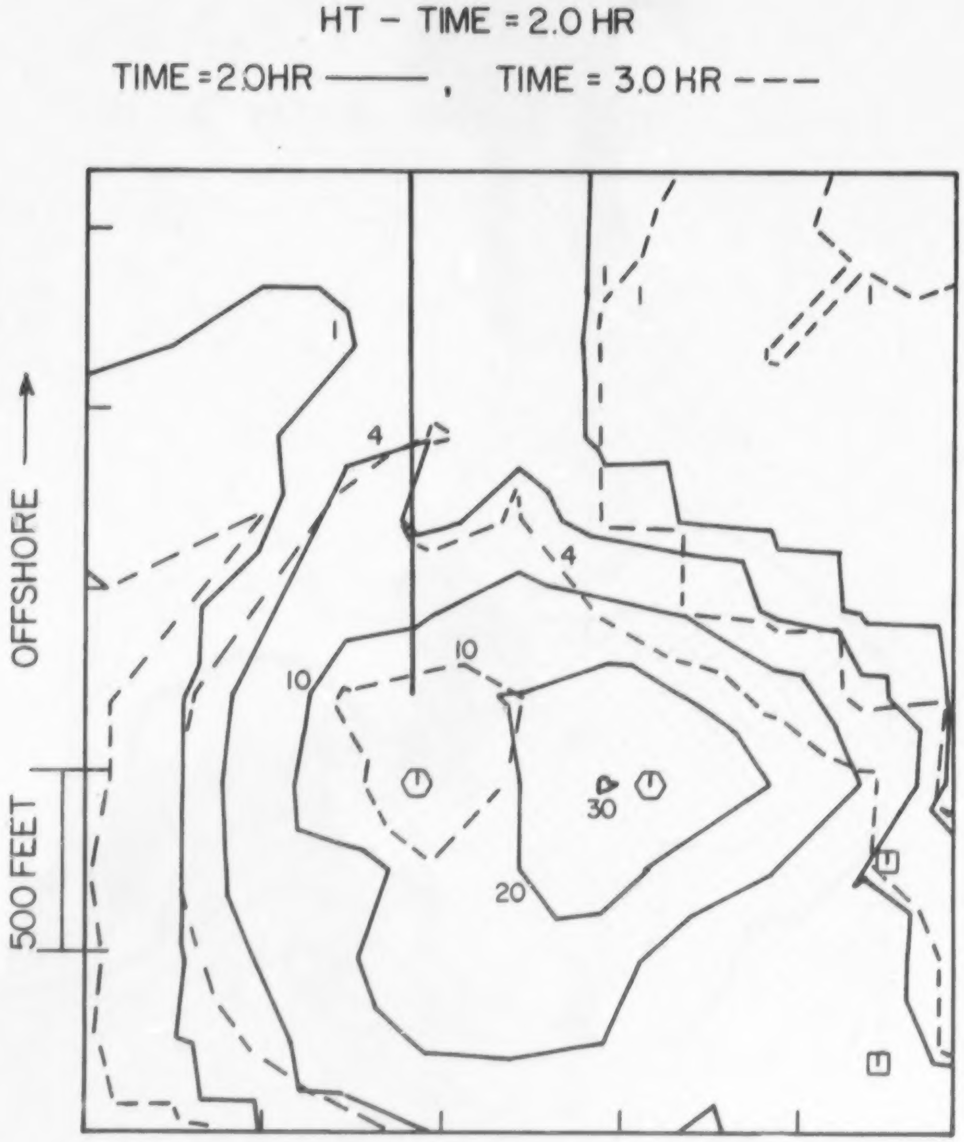

Figure 5. Surface isothermal contour plots of Unit 2 intake heat treatment of 2.0 hour duration with $\Delta T_o = 70^oF$ and no ambient current. Time of plot: end of heat treatment (solid lines) and 1.0 hr after end of heat treatment (dashed lines). All temperatures in ^oF above ambient.

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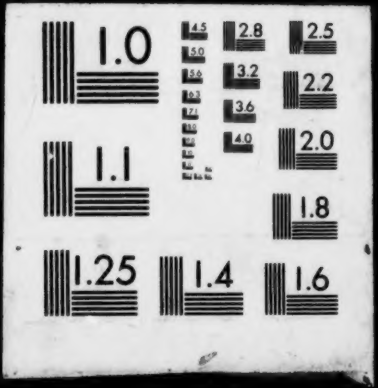
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6.3
7.1
8.0
2.8
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1.8
1.25
1.4
1.6

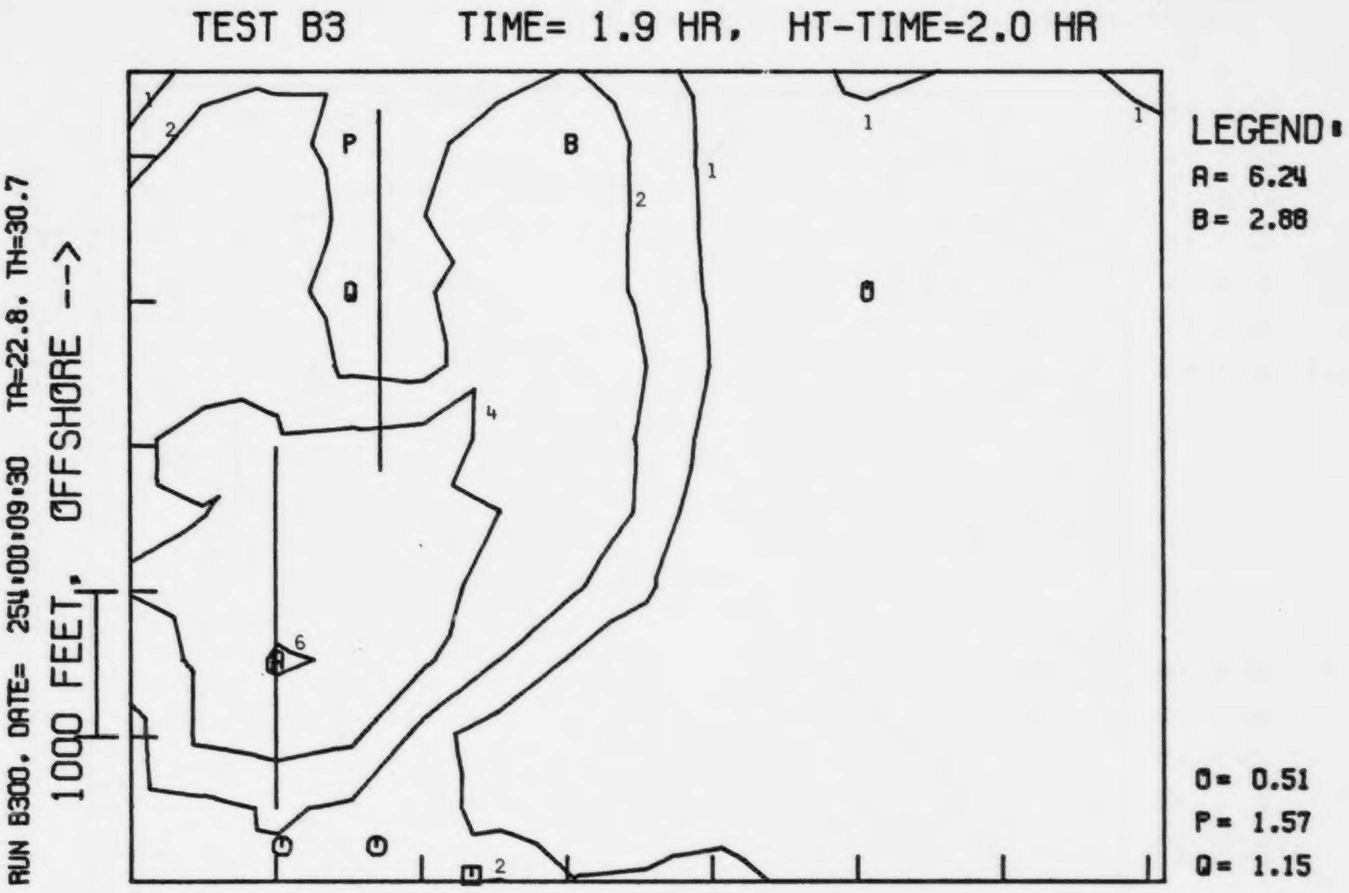

Figure 6. Surface isothermal contour plot of Unit 3 diffuser heat treatment of 2.0 hour duration with $\Delta T_o = 70^\circ F$ and no ambient current. Time of plot: 1.9 hour after start of heat treatment. All temperatures are given in °F above ambient.

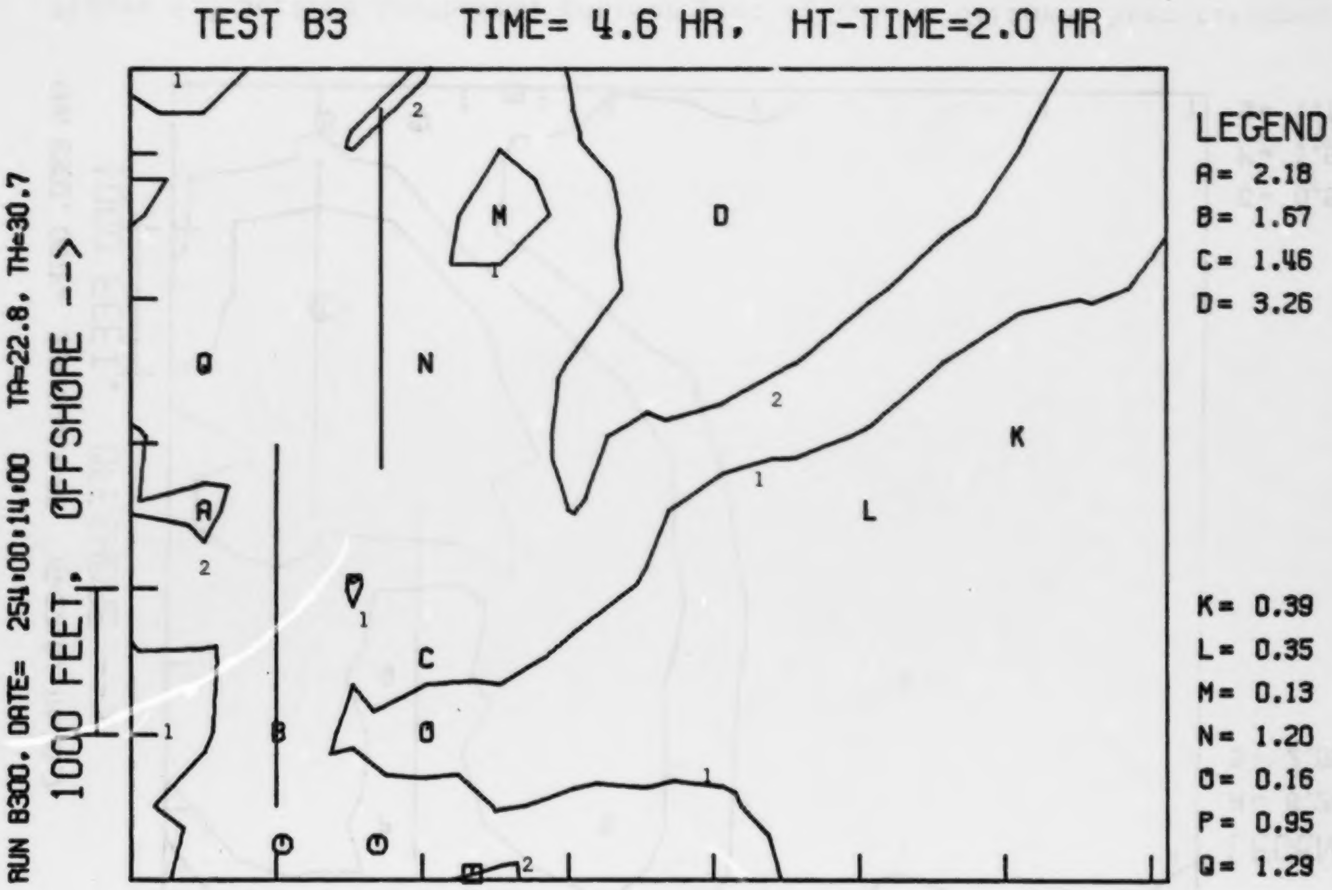

Figure 7. Surface isothermal contour plot of Unit 3 diffuser heat treatment of 2.0 hour duration with $\Delta T_o = 70^oF$ and no ambient current. Time of plot: 2.6 hour after end of heat treatment. All temperatures are given in ^oF above ambient.

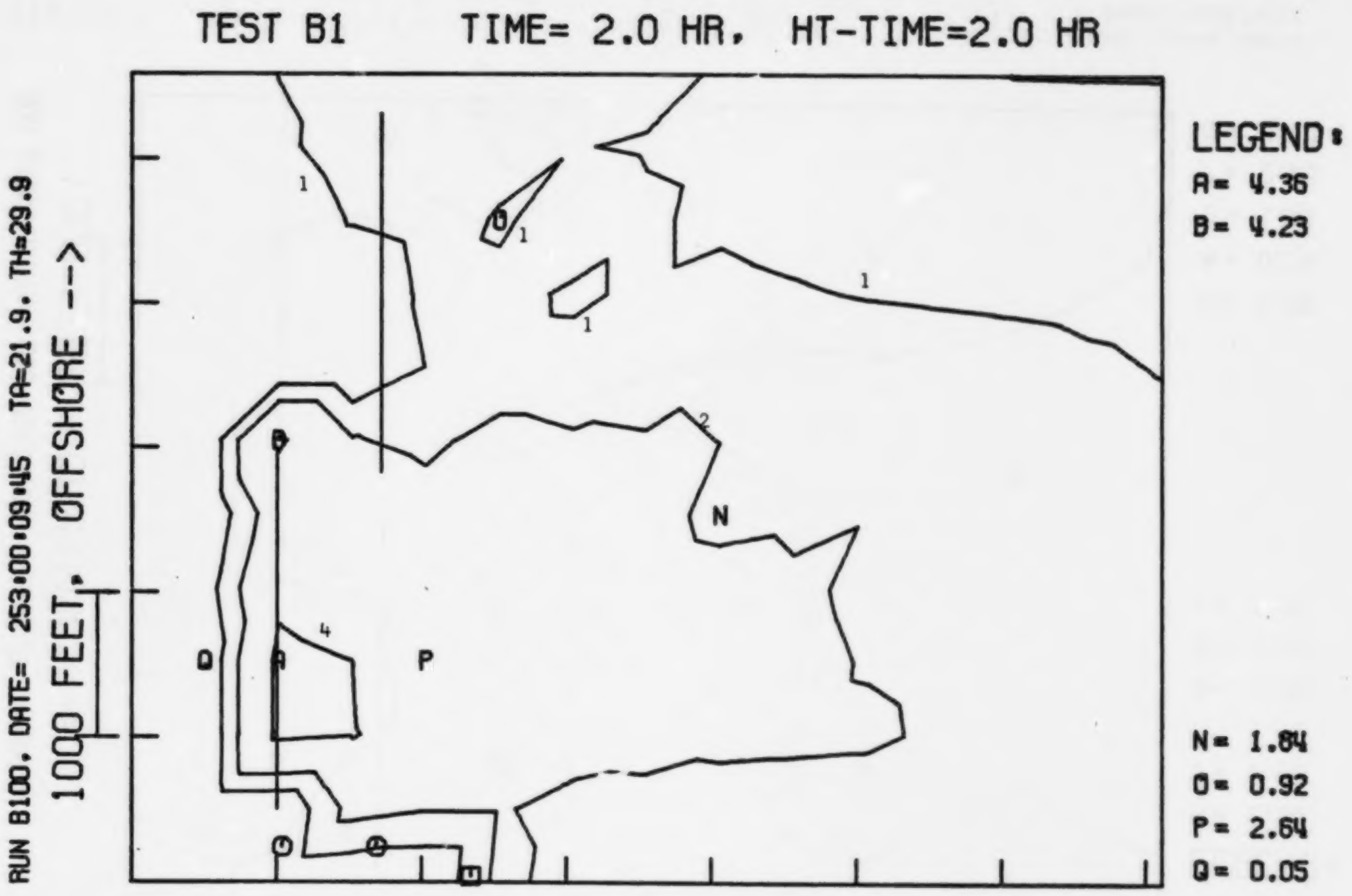

Figure 8. Surface isothermal contour plot of Unit 3 diffuser heat treatment of 2.0 hour duration with $\Delta T_o = 70^oF$ and a steady 0.3 knot ambient current (from left to right). Time of plot: end of heat treatment. All temperatures are given in ^oF above ambient.

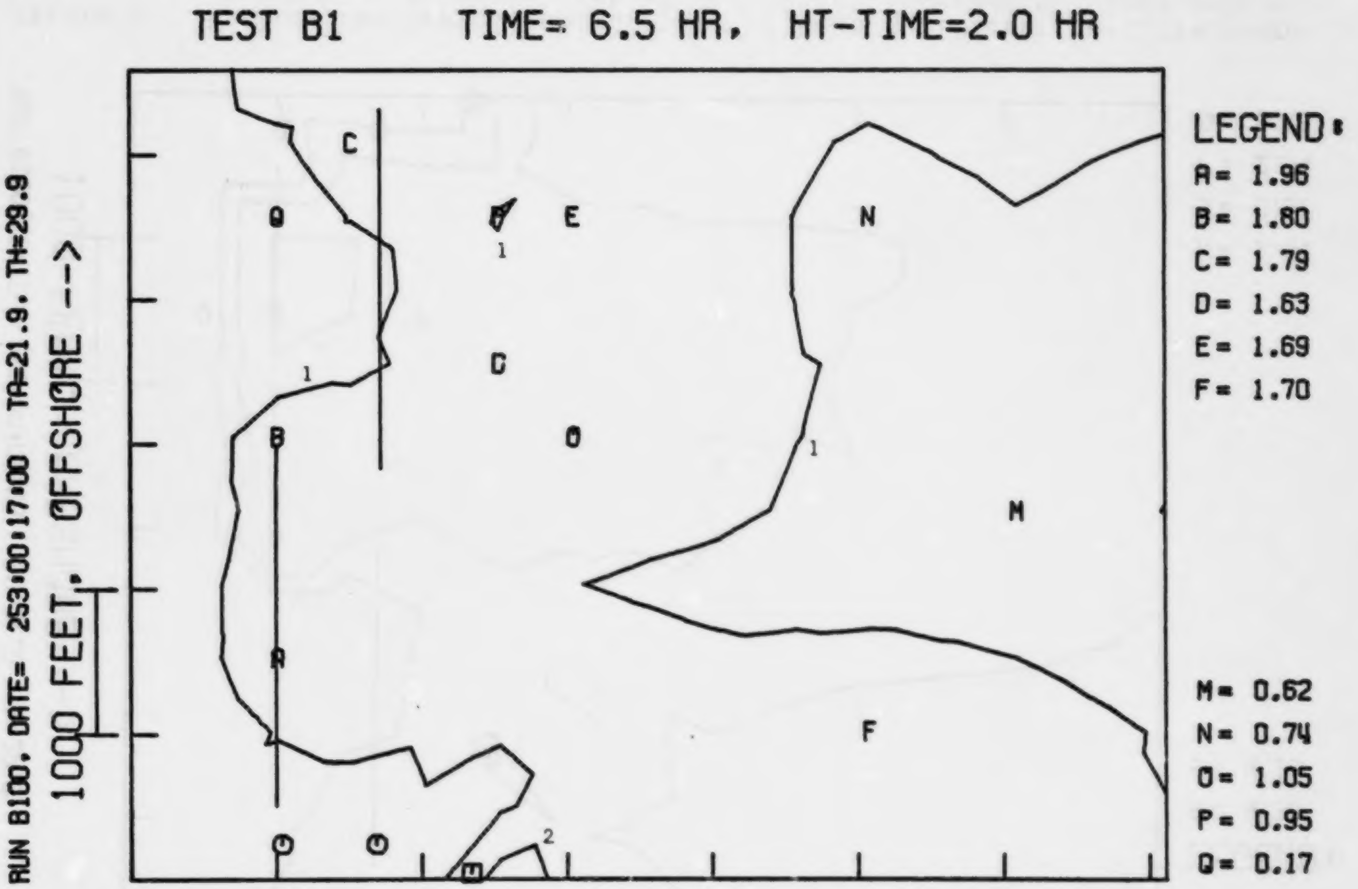

Figure 9. Surface isothermal contour plot of Unit 3 diffuser heat treatment of 2.0 hour duration with $\Delta T_o = 70^oF$ and a steady 0.3 knot ambient current (from left to right). Time of plot: 4.5 hour after end of heat treatment. All temperatures are given in ^oF above ambient.

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VIII-B-181

Abstract Submitted to the Conference on Waste Heat Management and Utilization, Miami Beach, Florida, May 9-11, 1977

LABORATORY INVESTIGATIONS ON SOME FUNDAMENTAL ASPECTS OF THERMAL PLUME BEHAVIOR

by

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ABSTRACT

A number of theoretical studies on the behavior of thermal effluents discharged into a body of water are available in the literature. Specifically, a number of "mathematical models" based on a variety of simplifying assumptions have been developed to predict the characteristics of the discrete thermal plume that exists up to some distance downstream of an outfall. The results of some of these models have been compared with field data, while others have been compared with dye-visualization and mean-temperature data from laboratory simulations. It is difficult to assess the validity of the mathematical models based on the type of comparisons mentioned above, since often certain parts of the data themselves are utilized to compute certain empirical constants which are essential parts of the models.

Indeed, the validity of many of the assumptions, such as the value of the entrainment "constants" and their dependence on such factors as ambient stratification, can be assessed only through detailed measurements (under controlled laboratory conditions) of the turbulence characteristics within the thermal plumes. An understanding of the turbulence characteristics is also essential for the development of improved models. For example, it has been suggested by some authors that, when discharge is made into a crossflow, the nature of the entrainment process on the forward

and leeward sides of the plume must be different. Very little is known about this "sheltering" effect. Again, while it is known that stratification influences the entrainment processes through horizontal surfaces, little is known about the actual functional dependence.

The present paper presents the results of laboratory studies on some of the fundamental aspects mentioned above. Specifically, detailed measurements of the turbulence statistics within thermal plumes due to surface as well as submerged discharges into quiescent and flowing environments are made with hot-film anemometers and fast-response thermistors. The experimental results are then utilized to examine many of the fundamental assumptions made in theoretical models.

Session VIII C

Case Studies I

7-45-11

CASE STUDIES
SOME SOLUTIONS TO THERMAL PROBLEMS IN THE SOUTHEASTERN USA

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ABSTRACT

Case studies of thermal pollution problems and proposed solutions at two Southeastern power plants are presented. One of the plants adjacent to the Gulf of Mexico was determined to cause substantial damage in the discharge area. The proposed solution is to move both the point of intake and the point of discharge further out into the Gulf. High temperature discharges from the second plant to a cooling lake and the large mixing zone size and location resulted in a determination that applicable water quality standards requirements were being exceeded. However, although some damages are evident, the 316 demonstration indicated the acceptability of continued once-through cooling under controlled operating conditions.

INTRODUCTION

Today, I would like to provide you with some insight into two thermal problems in the Southeast and to indicate how these problems have been or will be solved.

Before discussing the two specific plants, I would like to indicate the scope of 316 work underway in EPA Region IV.

Table I indicates that we have received applications for 160 steam-electric power generating plants of which 138 are presently in operation. On February 28, 1977, there were 34 demonstrations under 316(a) and 70 under 316(b) at various stages between implementation and approval. At that time, 20 of the 316(a) studies had been completed as had 35 of the 316(b) studies. We had approved 12 of the 316(a) demonstrations and 13 of the 316(b). Approximately 15 additional 316(a) and/or 316(b) studies can be anticipated in the near future for plants which have not yet been issued permits by states with NPDES authority.

Now that I have indicated the magnitude of the effort in Region IV, I would like to discuss two specific cases.

CRYSTAL RIVER PLANT

Figure 1 shows the general site of the Crystal River Plant of Florida Power Corporation. The site is about 70 miles north of Tampa, Florida and adjacent to the Gulf of Mexico. It lies about two miles south of the mouth of the Cross Florida Barge Canal. Units 1 and 2 are fossil-fired with a combined capacity of 900 Megawatts and are about 10 years old. Unit 3 is nuclear-fueled with an ultimate design capacity of nearly 900 Megawatts. Unit 3 has recently received its full power license from the U.S. Nuclear Regulatory Commission (NRC). Maximum three-unit operation increases the heat discharged to the Gulf of Mexico by 250 percent over two unit operation and flow is slightly more than doubled. Composite flow for all three units is about 1,318,000 gallons per minute (2940 cfs). The composite temperature rise above inlet is about 14.5F (8.1C) at maximum load.

The plant drafts water from the Gulf via a 15-foot deep dredged intake canal. This canal originally had a spoil dike along its northern edge extending about 6-1/2 miles into the Gulf. Nature has caused breaks in the dike and at present it is continuous to about 4-1/2 miles from shore except for one break at about 3-1/2 miles from shore. The southern edge of the intake canal has a spoil dike for a distance of about two miles from shore.

The discharge canal is dredged to a depth of ten feet for a distance of about one mile from shore but is diked along its southern edge only.

Comprehensive studies were needed to project the environmental impact of Unit 3 for NRC and to allow development of the NPDES permit by EPA. To assist in the development of the study plans, an interagency advisory committee was established in early 1973 with participants from EPA, NRC, Fish and Wildlife Service, National Marine Fisheries Service, National Parks Service, and the State of Florida. The study was instituted by consultants for Florida Power Corporation in late 1973. Of necessity, these studies were conducted with Units 1 and 2 in operation. Interim progress reports were prepared and reviewed and guidance was provided to Florida Power Corporation by the committee.

Evaluation of the completed study results in late 1974 led EPA to a finding that "substantial damage" as provided in the Florida Water Quality Standards was occurring due to the existing discharge from Units 1 and 2 and increased damage due to Unit 3 was expected. These damages to the discharge estuary are summarized in Table II.

In addition to the thermal damage, there are large numbers of post-larval stages of shrimp, stone crabs and blue crabs being entrained by the cooling water system and passed through the condensers. By large numbers, I mean in the billions of organisms of each species each year.

Given the problem, the next question is what is the solution? One solution, of course, is cooling towers. However, the Company has proposed intake/discharge modifications shown in Table III.

The first three items of discharge canal modification would remove the thermal discharge from the more productive near shore area to reduce the major thermal impact. The remaining two items would remove the intake source from the near shore nursery area and would reduce intake velocities in the intake canal. Both of these latter items would reduce intake damage.

EPA concurs with the Company that the proposed modifications have a good chance of reducing or eliminating the thermal and intake problems. Negotiations as to the specific details of the fill and dredge project are presently underway. Thermal effects and impingement/entrainment monitoring will be required after the project is completed to assure that impacts have been minimized.

H.B. Robinson Plant

The second plant I would like to discuss is shown on Figure 2. This is a view of Lake Robinson, a 2,250-acre cooling lake, constructed in 1959 by impounding Black Creek. The H.B. Robinson Plant of Carolina Power and Light Company is located about 55 miles east-northeast of Columbia, South Carolina. Unit 1 is a 185 megawatt coal-fired unit which was placed in operation in 1960. Unit 2 is a 730 megawatt nuclear-fueled unit which began operation in 1971. Originally, the discharge entered the lake about one mile from the plant. Canal length was increased to about four miles during the construction of Unit 2 and is now in the upper reaches of the impoundment.

In the vicinity of the discharge, surface temperatures in excess of 102F(30C) have extended across the entire surface width. Temperatures exceeding 90F(32C) have been observed across the entire width of the lake to a depth of eight feet. More than 75 percent of the cross-sectional area of the lake was found to exceed 90F in the vicinity of the discharge at that time. Since these temperatures and mixing zone requirements exceed applicable water quality standard requirements, the Company conducted a one-year study in an attempt to demonstrate that continued once-through cooling was compatible with assuring the "protection and propagation of a balanced indigenous population of shellfish, fish and wildlife" as provided by Section 316(a) of P.L. 92-500.

On review of the 316 demonstration, EPA and the State of South Carolina found that the thermal discharge was causing some adverse impacts on the aquatic populations of Lake Robinson. However, notwithstanding these adverse effects, we concluded that a balanced indigenous population exists in Lake Robinson which is generally typical of other similar, heated and unheated lakes in the southeast. EPA further concluded that a serious potential for severely increased damage exists if the thermal component of the discharge were increased above historical levels. The permit contains thermal limitations consistent with the historical operation of the plant, but provides constraints to continuous operation of the plant at high load factor for extended periods. These limitations established are the most complex which have been applied to any thermal discharge in the southeast, but they are warranted due to the thermal loading on Lake Robinson. Thermal limitations are shown on Table IV.

It can be seen from Table IV that maximum discharge temperature limitations have been established for each month of the year and for the maximum day in each month. Summer discharge temperatures at the plant were very high. The maximum 24-hour average temperature observed was 111F and the maximum 30-day average temperature was almost 109F. Although the hottest temperatures which occurred during the demonstration were in August, the Company noted the possibility that maximum temperatures could occur during virtually any summer month as a function of meteorology, hydrology and power demand. During the summer months we were most concerned about the absolute value of the maximum temperatures and the general pattern of temperature rise and heat addition. We were not generally concerned with the particular month of maximum temperature occurrence since "living space" for the fishery was the governing function rather than reproduction and fry development. Therefore, to assure flexibility for the Company and still protect the aquatic populations, roving maximum discharge temperatures were established for 30-, 60-, 90- and 120-day periods during the summer months consistent with historical averages. Restrictions on the actual amount of heat discharged to the impoundment further protects the thermal regime by assuring that the natural cyclical pattern of climactic conditions is maintained.

Details of the EPA determination are beyond the scope of this discussion, but a copy can be obtained by writing to me in Atlanta.

TABLE I

316 DEMONSTRATION STATUS
FEBRUARY 28, 1977
STEAM-ELECTRIC POWER PLANTS
U.S. EPA REGION IV

Number of NPDES Applications: 160

Number of Operating Plants: 138

Demonstration Status	316(a)	316(b)
Total Number	34	70
Studies Completed	20	35
Demonstrations Approved	12	13

Near Future Studies Not Yet Underway: 15

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TABLE II

THERMAL DAMAGES
CRYSTAL RIVER POWER PLANT

1. Conversion of the inner and outer bays from benthic-dominated systems of rooted plants and macroalgae to plankton dominated systems,
2. Reduction of gross primary production in the 175-acre inner discharge bay,
3. Reduction in standing crop and diversity of benthic grasses and macroalgae,
4. Reduction in microinvertebrate biomass by five-fold in the discharge estuary,
5. Exclusion of 29 species (20 percent) of macroinvertebrates, and
6. Exclusion of over 40 percent of the fish species found in the site vicinity.

TABLE III

PROPOSED CORRECTIVE ACTIONS
CRYSTAL RIVER POWER PLANT

Discharge Modifications

1. Extend the 10-foot deep discharge canal to a distance of about two miles from shore
2. Extend the south dike of the discharge canal to a distance of about two miles from shore
3. Construct a parallel northern dike

Intake Modifications

1. Extend the intake canal to a distance of about 3-1/2 miles from shore and deepen the extended intake canal to 19 feet
2. Extend the south dike of the intake canal to a distance of about 3-1/2 miles from shore

204<
CHK

TABLE IV

H.B. ROBINSON, THERMAL EFFLUENT LIMITATIONS

	Maximum 30-day Average	Maximum 24-hour Average	Instantaneous Maximum
Discharge Temperature-C(F)			
June-September	1/	44.0(111.2)	-
October	35.5(95.9)	37.5(99.5)	-
November	30.0(86.0)	33.0(91.4)	-
December-February	26.0(78.8)	29.5(85.1)	-
March	30.0(86.0)	32.0(89.6)	-
April	32.0(89.6)	35.0(95.0)	-
May	34.0(93.2)	37.0(98.6)	-
Heat Discharge (BTU/hr)	5.50×10^9	-	6.28×10^9
Dam Release Temperature-C(F)	-	33.0(91.4)	-

1/ Maximum discharge temperature shall not exceed the following limitation for the periods specified, as a roving average, during the months of June through September: 30-day - 42.6(108.7), 60-day - 41.7(107.1), 90-day - 41.3(106.3), and 120-day - 40.2(104.4).

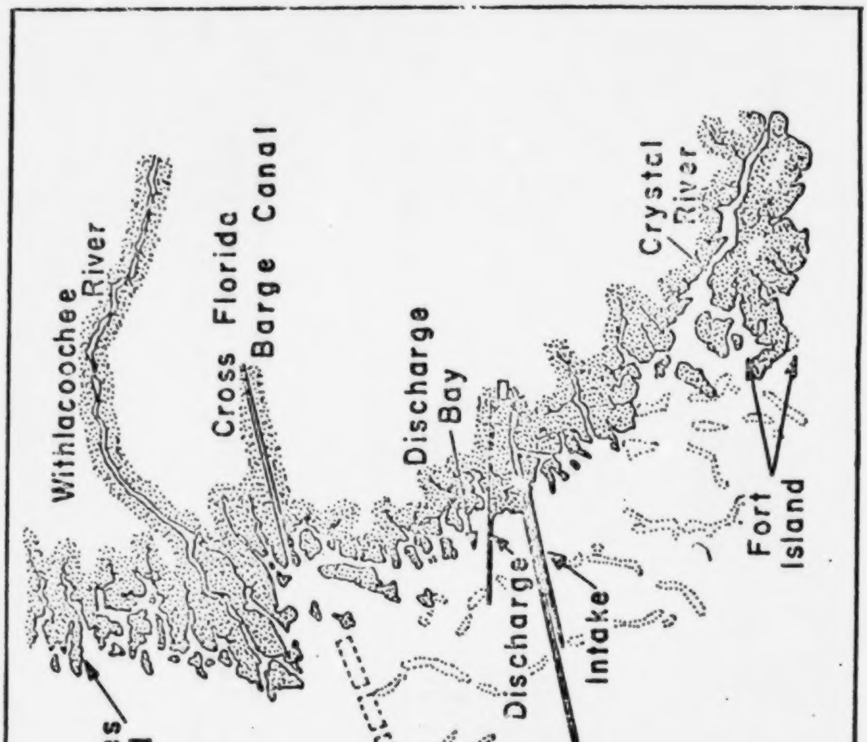
Withlacoochee River
Cross Florida Barge Canal
Discharge Bay
Crystal River
Fort Island
Intake
Discharge
Hodges Island
Spoil Islands
N
0 1 2 3
Kilometers
0 0.5 1
Nautical Mile
Tampa
Crystal River Power Plant
0 100
Miles

Figure 1. Crystal River Power Plant Site Area

206<

CHK

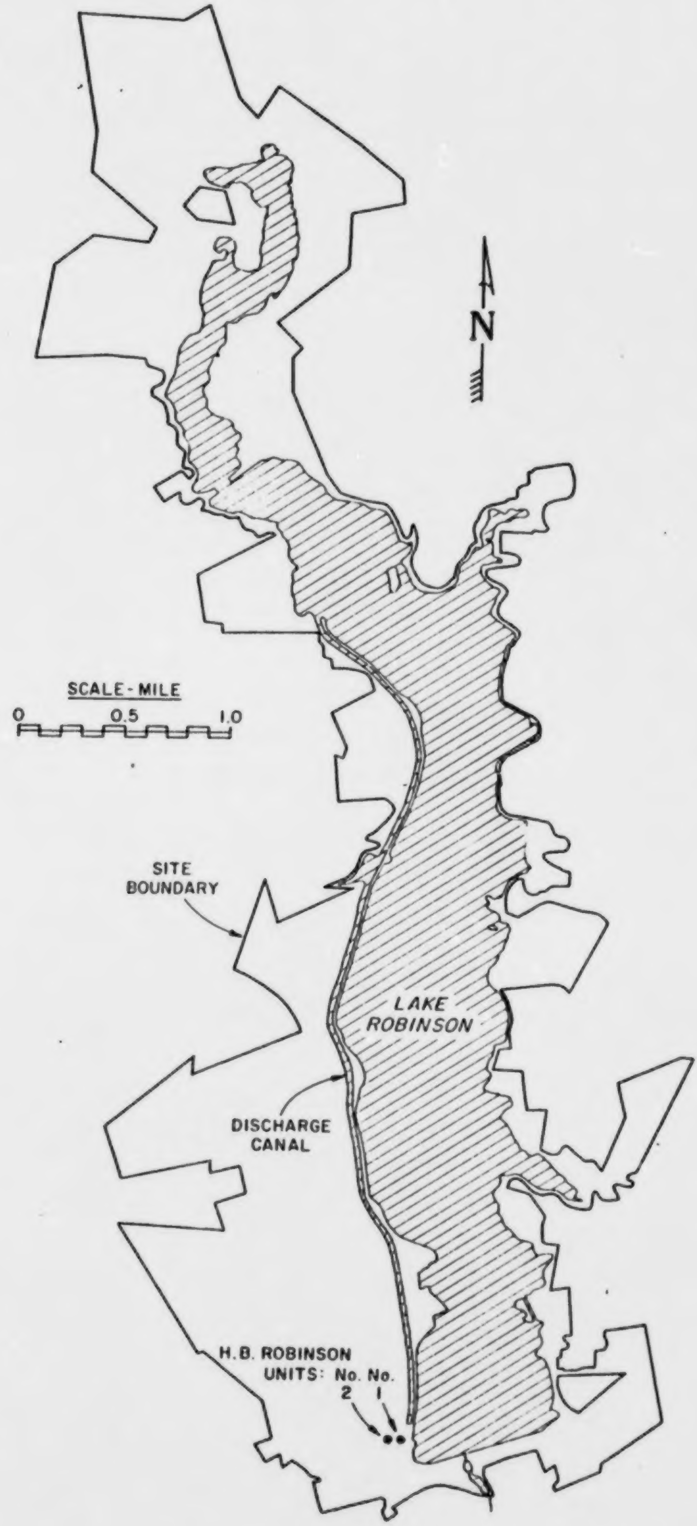
N
SCALE - MILE
0
0.5
1.0
SITE
BOUNDARY
LAKE
ROBINSON
DISCHARGE
CANAL
H.B. ROBINSON
UNITS: No. No.
2
1

Figure 2. Robinson Power Plant Site Area

VIII-C-197 8-45-19

WASTE HEAT IN THE CENTRAL ELECTRICITY GENERATING BOARD

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ABSTRACT

In the United Kingdom the Central Electricity Generating Board operates 56 GW(e) of water-cooled thermal plant. Over more than a decade it has mounted a programme of research into the engineering, physics and biology of waste heat removal to assess and minimise the environmental consequences and, more recently, to exploit the discharges where possible.

"Before and after" ecological surveys have revealed no trends discernible above natural year-to-year and season-to-season variations. Theoretical studies have been made of the factors limiting heat dissipation from large ($\sim$GW(e)) concentrations of coastal generation. The environmental impact of the hyperbolic convective wet cooling tower has been notably reduced by the development of a fan-assisted design presently under construction at Ince. The cost of reduction of plume visibility by the incorporation of dry stages has been assessed.

To assist the exploitation of warm water discharges, the Board has mounted programmes of experimental eel, trout and carp culture in which commercial interest has been shown. It is also evaluating the problems of utilising waste heat for greenhouse crops. The potential use of waste warm water in sewage plant and of nitrification processes in cooling towers are being evaluated.

INTRODUCTION

The problems of economic and environmentally acceptable disposal of waste heat span across almost the whole of the Board's organisational structure, involving the Planning Department, the Generation Development and Construction Division, the Research Division and the Regional Scientific Services Departments. Much of the work is specific to particular sites. This paper attempts to summarise the more generic content and therefore draws more heavily on the Board's research work, particularly that carried out at the Central Electricity Research Laboratories and its biological outstations.

THE ECOLOGICAL IMPACT OF COASTAL AND ESTUARIAL STATIONS

The trend of power station siting in the U.K. over the past decade or so has been towards coastal and estuarial sites. These now account for 29,000 MW(e) of the capacity installed or under construction, including several 2000 MW(e) stations. The CEGB has over the same period mounted a programme of research and surveys to monitor and understand the physical and ecological effects of the warm water discharges from its stations. |1-6|

It has established that the thermal perturbation from the stations is generally small compared with the solar, wind and tidal temperature influences. This is particularly true in the case of estuarial shoals. Inshore coastal water temperatures around the U.K. show seasonal variations of at least 10K with tidal fluctuations superimposed. Longer term trends of up to 5K have also been noted in the North Sea and English Channel. |7,8| It is known that the occurrence abundance, and geographical distribution of marine organisms are influences by these long-term natural trends in water temperature |8-10| , but also that inshore and estuarine organisms are adapted to tolerate the usual range of daily, tidal and seasonal variation. On occasions when the usual range is grossly exceeded - e.g. the very cold winter of 1962 - the fauna and flora are badly affected.

Against this background of variation in environmental conditions and variability in biological response, major ecological effects should probably not be expected to arise from the Board's warm water discharges and indeed have not been found in the several longstanding surveys by the CERL Biology Section at CEGB sites. This is well illustrated in the case of Bradwell where public concern was expressed at the proposal to build a Nuclear Power Station on the grounds that both the ecology of the Blackwater Estuary, and the health of oyster stocks would be adversely affected. As a consequence, continuing surveillance of the general ecology and the oyster beds was a condition of consent for building and operating the station. Preliminary surveys of hydrography, plankton, benthos, littoral habitats, commercial fish and shell fish stocks were made prior to commissioning |11|, and subsequently at intervals. This sequence of observations was interrupted by the cold winter of 1962-63 which devastated the populations of benthic, littoral and intertidal organisms, including the oyster stocks. The distribution and abundance of organisms in 1963 differed substantially from that found earlier, but later surveys have given ample demonstration that natural forces were responsible and have established the recovery of the estuary from the 1962 devastation. Although the station has operated consistently throughout the intervening 15 years, discharging $\sim 24\ m^3s^{-1}$ of cooling water and raising overall temperature in the surface water by 0.2 - 1.7K above ambient, there have been no adverse changes over this period. The commercial fishery returns have remained substantially constant, although shell fisheries have reflected changes in demand and other changes occurring elsewhere. No case has been made by the oyster fishermen that their stocks are damaged by increased temperature, by increased parasite depredation, or by entrainment of larvae |12|.

Substantial studies have also been made at Fawley and Marchwood on Southampton Water |13| and at Pembroke on Milford Haven |14|. In Southampton Water and the Solent the clam Mercenaria has become established close to the Marchwood Station outfall. An oyster fishery at Stanswood Bay, close to the Fawley outfall, has become a commercially viable industry following the restocking of beds in the adjacent Beaulieu River in the late 1960s. (Fawley Power Station was commissioned in 1969.) Thus far, 40 man years of field survey have failed to find evidence of adverse changes of any significance arising from the CEGB's thermal 'signals' amongst the natural 'noise' of the U.K. estuaries and coastline.

COOLING OF LARGE COASTAL GENERATING COMPLEXES

To help assess the likely impact of much larger discharges, a simple mathematical model has been developed, following earlier work of Scriven [15] and Macqueen [16,17], to represent the temperature field arising from a large direct cooled generating complex situated on an open coastline. The essential features of the model are shown in Figure 1. The station is represented by a vertical line source discharging water at a rate V and at a temperature elevation of T_o into open sea of uniform depth h. A tidal excursion of $\pm a$ along the coast is superimposed on a tidal drift of velocity u_d. Water returns to the station from an intake at distance b offshore. Vertical mixing is assumed to be instantaneous. The heat is transported away from the source by the combined effects of offshore diffusion, K_y; the offshore displacement of warm water; advection by the drift current and transfer to the atmosphere at a rate αT per unit area where T is the local water temperature elevation and α a coefficient dependent on meteorological conditions.

The time constant for surface cooling τ is given by $\rho c h \alpha^{-1}$ where ρc is the specific thermal capacity of water. Under conditions typical of the U.K. coastline τ is of the order 30 hours, i.e. several times the tidal period. The overall effect of the tidal oscillation is therefore to smear the thermal source over a distance 2a with a distribution properly weighted to take account of the tidal wave form.

The equations governing this situation have been solved analytically using parameters illustrative of coastal conditions in the United Kingdom. Measurements commissioned by the CEGB off the East Anglian coast have shown tidal drifts in the range 0.02 - 0.10 ms^{-1} [18]. Dye patch measurements in the same locality by Talbot [19] over a few hours give values of K_y approaching 2 ms^{-1}. Larger values may well be operative over the more extended times and circulations envisaged in the present model. Examples of the results are shown in Figures 2-4, in each case, for a 10 GW(e) station discharging 500 m^3s^{-1} at a temperature excess of $T_o = 10K$, $a = 5$ km, $b = \infty$ and $\alpha = 25\ Wm^{-2}k^{-1}$.

Figures 2a and b both show the large effect of small drift velocities in reducing the shoreline temperature and the offshore extent of the thermal field. The effect of a high thermal diffusion coefficient in lowering shoreline temperatures is also brought out.

The development of the thermal field downdrift of the source is illustrated in Figures 3a and 3b for cases of low and high thermal diffusion respectively. In these cases, as in those of Figure 2, the shoreline temperatures and extent of the temperature field would be smaller with greater depths of water.

In practice, power station discharges are made some distance offshore. Moreover, momentum and buoyancy forces will spread the warm discharge in a stratified way over a considerable area before substantial thermal mixing takes place with the tidal stream. In the case of the Sizewell 430 MW(e) station, this distance is some 500m offshore, while in the case of a 10 GW(e) station, it could easily be 1 km or more. The effects of various locations or distributions of the discharge can be explored in a simplified way using the model and some illustrative results are given in Figure 4 where curve a corresponds to a shoreline discharge, curve b to a discharge distributed over 1 km offshore and curve c to a discharge point located 1 km offshore. It can be seen that acceptable shoreline temperatures can be obtained with practical offshore locations of the discharge.

In all the cases presented, station intake is assumed to be completely outside the temperature field, but the equations can be solved for the general case of an intake at a finite distance offshore. In practice, to maximise station efficiency, care is taken with the siting of the intake to avoid re-entrainment, taking advantage of such factors as local sea bed topography and thermal stratification. The curves presented should approximate the case of a well sited intake.

It will be evident that the successful prediction of the temperature field from a large coastal generating complex will depend sensitively on an accurate knowledge of the residual drift currents and diffusion coefficients over a considerable area offshore from the complex. From existing Admiralty data it is known that the drift patterns are subject to seasonal changes and no doubt to wind forces. The diffusion coefficient is likely to be subject to similar variations. To provide field data, the Generation Construction and Development Division of the CEGB has recently commissioned a very detailed survey of tidal currents and temperatures near Sizewell in Suffolk. Extending over a period of six months, it covered an area of some 50 km^2 and involved more than a dozen meters reading current and temperature at 10 minute intervals, supplemented by wind and pressure data, dye and float track releases and information from lightships. The results, when processed, will form an extensive data base for comparison with simple models such as the one outlined and with the more elaborate coastal flow models such as that developed by the Hydraulics Research Station at Wallingford |20|. Further development of such models to include heat transfer to the atmosphere is now under way, drawing on the results obtained in a seven-year study of the thermal balance of Lake Trawsfynnyd in North Wales, the site of one of the CEGB's nuclear power stations |16, 21|.

COOLING TOWER DEVELOPMENT

For inland sites where direct cooling is not possible, CERL research has been directed to minimising the visual impact of cooling towers in the landscape. The conventional natural draught wet cooling towers used in the U.K. during the 1960s would typically have a height of 114m and a base diameter of 91m and would be capable of handling the waste heat from 250 to 330 MW of electrical generation.

A 2,000 MW(e) station therefore required 6-8 such towers. With the object of reducing the number of towers, a development programme was mounted aimed at designing a minimum cost, minimum size, fan assisted tower capable of handling 1000 MW(e). In striking a balance between initial capital cost and fan power costs the following design features emerged:-

a. For the same heat transfer performance, a cross flow splash packing entailed significantly lower air flow resistance. Numerical computation methods were therefore developed for predicting cross flow packing performance - thermal and aerodynamic |22|.

b. To minimise the overall diameter and influence of external cross winds, it proved advantageous to site the fans down-stream of the wet packing in spite of the more arduous operating and maintenance environment.

The design concept of the Assisted Draught Cooling Tower (ADCT) is shown in Figure 5.

To confirm the Laboratory predictions of packing and fan performance, a replica of one cell was constructed in which the full scale performance of the heat transfer packings, the water droplet eliminators and the proposed axial flow fans were all investigated. The geometry of the packing and the water distribution system was finalised using this cell.

On the basis of these tests, a tower design was proposed for the 1000 MW(e) 'B' station to be constructed at Ince in Cheshire, involving a shell 114m high by 94m in base diameter, surrounded by a podium structure of height 14m and external diameter 172m housing 35 cooling cells. A 1/125th scale model of this tower was built and aerodynamically tested in the CERL wind tunnel in both natural draught and assisted draught modes. It was shown that, in the latter mode, a cross wind of 17 ms^{-1} would result in a reduction of 1% in the station output. Fan power at full cooling duty was estimated at 6 MW(e) and, initial capital cost at 85% of an equivalent natural draught cluster. The design was in fact adopted for Ince 'B' and construction is now nearing completion |23,24|.

The optimum design of an assisted draught cooling tower is related to the condenser specification, the ambient temperature, humidity and pressure at the location, as well as to seasonal load factors. A computer programme has therefore been written to facilitate the selection of the cheapest geometrical arrangement of an ADCT for a given duty within specified limits of shell and packing size.

With a view to further reduction of visual impact, a further study has been made of the cost/benefit of reducing plume visibility from an ADCT by the incorporation of dry cooling components in parallel with the splash packings. Using design data for the Ince 'B' tower, the cost of including dry coolers occupying up to 50% of the total perimeter of an equivalent hybrid ADCT has been estimated. The corresponding plume visibility was assessed in the following way. It was first postulated that plumes would only be conspicuous when low cloud cover was less than 6/8ths for a period of one hour or more. Meteorological records were used to derive the number of such days in a year for a specific location in which the cloud, temperature and humidity conditions, coupled with the tower exit conditions, would lead to plume formation. In each case, exit conditions corresponding to 0, 20, 30, 40 and 50% of dry packing in the periphery were used. The corresponding tower sizes, capital costs and plume frequencies are shown in Table 1. It will be seen that a large increase in total capitalised costs is entailed in making a substantial reduction in plume frequency.

EXPLOITATION OF WASTE HEAT

The economic, climatic and sociological conditions in Great Britain do not favour the large-scale use of waste heat from power stations for domestic or industrial heating purposes. The CEGB is, however, exploring the potential of its warm water discharges, for the acceleration of biological processes where a 10K rise may be very significant.

For some time facilities have been made available at three of its nuclear stations - Trawsfynnyd in North Wales, Wylfa in Anglesey and Hinkley in Somerset - for the experimental aquaculture of trout [25], sea trout, prawns and oysters. In Scotland, the White Fish Authority have mounted a substantial trial of sole and turbot at the Hunterston nuclear power station.[26]

CERL, at its Freshwater Biology Unit at Ratcliffe-on-Soar Power Station, has been investigating the growth of eels and carp in warmed river water [27,28]. Eels were chosen particularly because they were known to be able to survive at high temperatures and to tolerate if necessary relatively high concentrations of chlorine and ammonia and low concentrations of dissolved oxygen. Trials have been carried out on the comparative growth of eels in water taken directly from the River Trent, in the water from the cooling tower ponds and in water direct from the station condensers. Over a period of a year, the temperature ranges were respectively 5-25°C, 10-25°C and 15-35°C. Ammonia levels ranged between 0.4 and 2.3 ppm in the river and between 0.07 and 0.56 ppm in the cooling circuit. Dissolved oxygen levels in the fish tanks were generally above 6 ppm and normally 0.5 - 1.0 ppm higher in the cooling circuit water than in the river water. Normal chlorine additions to the condenser water gave levels around 0.5 ppm for up to 20 minutes periodically, but the concentration in the tanks was substantially less. All the eels were fed to excess on the same proprietary pellets containing approximately 50% raw protein and 6-11% fat. The comparative growth rates of the eels in the three water conditions is illustrated in Figure 6 [28]. Attention is now being given to determining the optimum temperature, by blending pond and condenser water, and to the optimum diet.

The world consumption of eels is estimated to be in excess of 50,000 tons per year and rising. Wild stocks are becoming heavily exploited and the vigorous eel trade is looking to eel farming to make up the shortfall. Commercial negotiations for eel farming facilities are now under way at some of the Board's inland power stations where there is sufficient warm water available to sustain a significant fraction of the world's eel demand.

Carp are even easier to rear than eels, growing quickly on a relatively low protein diet. Figure 7 |28| shows results obtained at Ratcliffe. However, unless the British public develops a taste for smoked carp to match that in some East European countries, the commercial outlet for reared carp in the U.K. would appear to be limited to sporting fishing.

Horticultural applications of waste warm water are being re-evaluated in the wake of the rising cost of oil (fuel costs currently represent 35-40% of the market price of tomatoes in Great Britain). With this incentive, the North Eastern Region of the CEGB has mounted a project, at the Eggborough Power Station in Yorkshire, to develop and evaluate low cost heating systems for greenhouses, including both direct contact evaporative air heaters and fan assisted convectors |29|. Initial crops include tomatoes and winter lettuce and the evaluation will continue during the 1977 season using three polythene tunnel greenhouses 5m x 36m in ground area.

Possibly the largest scale biological process engineered in the developed countries is the treatment of sewage to separate solid matter and to reduce the BOD and COD of the effluent discharged to rivers. Such purified effluent has been used as makeup water for cooling towers for many years in power stations throughout the world.

In the conventional activated sludge sewage treatment plants used in the U.K., the rate of the aerobic microbial oxidation and nitrification processes approximately doubles for a 10K rise in temperature. In winter the nitrification stage is often not fully effective and the NH_3 level in the effluent generally rises. It has long been known that dissolved ammonia is oxidised in the highly aerated water of cooling towers |30|. Opportunity has therefore been taken at Croydon Power Station to investigate in some detail the bacterial nitrification processes which are active in normal tower operation. The species responsible for the conversion of ammonia to nitrite is Nitrosomonas while Nitrobacter continue the process to nitrate. It has been shown that both species colonise the tower packings, the pond sediment and the suspended solids and that they survive intermittent injection of chlorine as well as prolonged shutdown periods in cold weather |31|. Even in winter months, the tower will accept a 2% makeup stream containing some 30-40 ppm NH_3 while maintaining the level in the circulating water at 1 ppm. It is unlikely that the oxidising potential of this tower is fully utilised since the dissolved oxygen in the water returning to the condensers is still close to 90% of saturation. Rig experiments are currently under way to determine the influence of major design and operating parameters on the capacity of micro-organisms for oxidation in such systems and to investigate the chemical consequences of this action for the plant.

Water Authorities in the U.K. are paying increasing attention to ammonia limits in sewage effluent discharges to inland rivers and the Thames Water Authority has collaborated actively in the work at

Croydon Power Station [32]. A possibility, arising from this work, for interlinking an inland 1300 MW station with a large sewage treatment plant is shown in Fig.8. The advantage to the treatment plant would lie in the degree of nitrification and oxygenation provided by the cooling tower and in the thermal acceleration of the treatment process by the warm return stream.

In recent years levels of nitrate in rivers have been rising throughout the world and the W.H.O. has recommended a nitrate limit of 11.3 ppmN. In response to this situation, the Thames Water Authority and the Water Research Centre in the U.K. have been investigating biological denitrification processes involving an anoxic stage before the conventional activated sludge stage. The same bacteria that utilise dissolved oxygen to achieve carbonaceous and nitrogenous oxidation can, under anoxic conditions, utilise the oxygen bound in the nitrate to achieve carbonaceous oxidation. The nitrate is first reduced to nitrite and thence to elemental nitrogen which escapes to the atmosphere. Successful experience is being obtained with a pilot scheme at the Rye Meads sewage plant [33].

The denitrification process would also benefit from thermal acceleration and an anoxic stage could in principle form the first section of the treatment plant shown in Fig.8. In this way, the nitrate formed in the tower would be converted to nitrogen gas and the final effluent to the river would be much lower in nitrate. This concept is being evaluated with the Water Authorities.

ACKNOWLEDGEMENTS

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TABLE 1

EFFECT OF INCREASING PROPORTIONS OF DRY COOLING ON THE SIZE, COST AND PLUME FREQUENCIES OF A HYBRID ADCT IN THE MANCHESTER AREA

% DRY PERIMETER	0	20	30	40	50
PODIUM DIAMETER m	172	195	208	223	241
RELATIVE COSTS	1.00	1.28	1.44	1.64	1.94
CONSPICUOUS PLUME FREQUENCY DAYS/YEAR	151	65	31	10	2

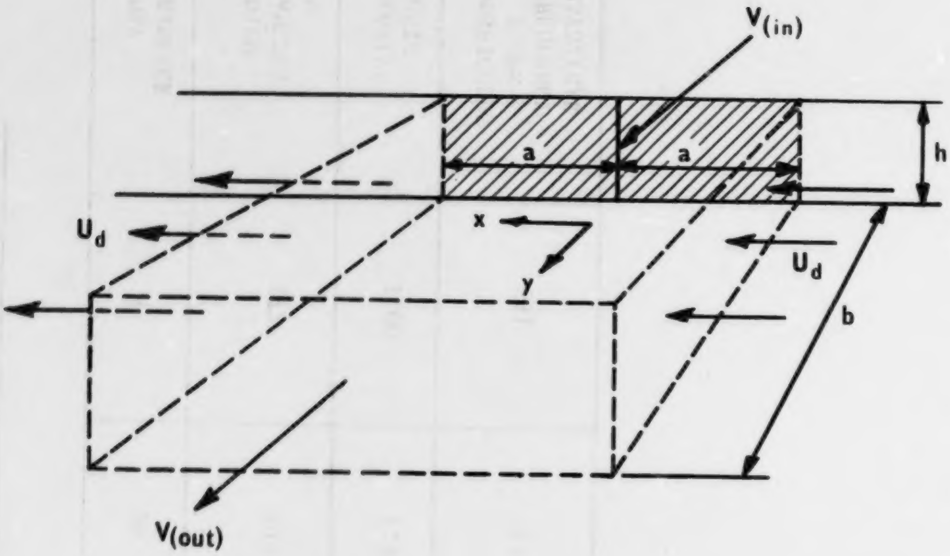
V(in)
a
a
h
U_d
x
y
U_d
b
V(out)

Fig. 1 Model of Coastal Discharge

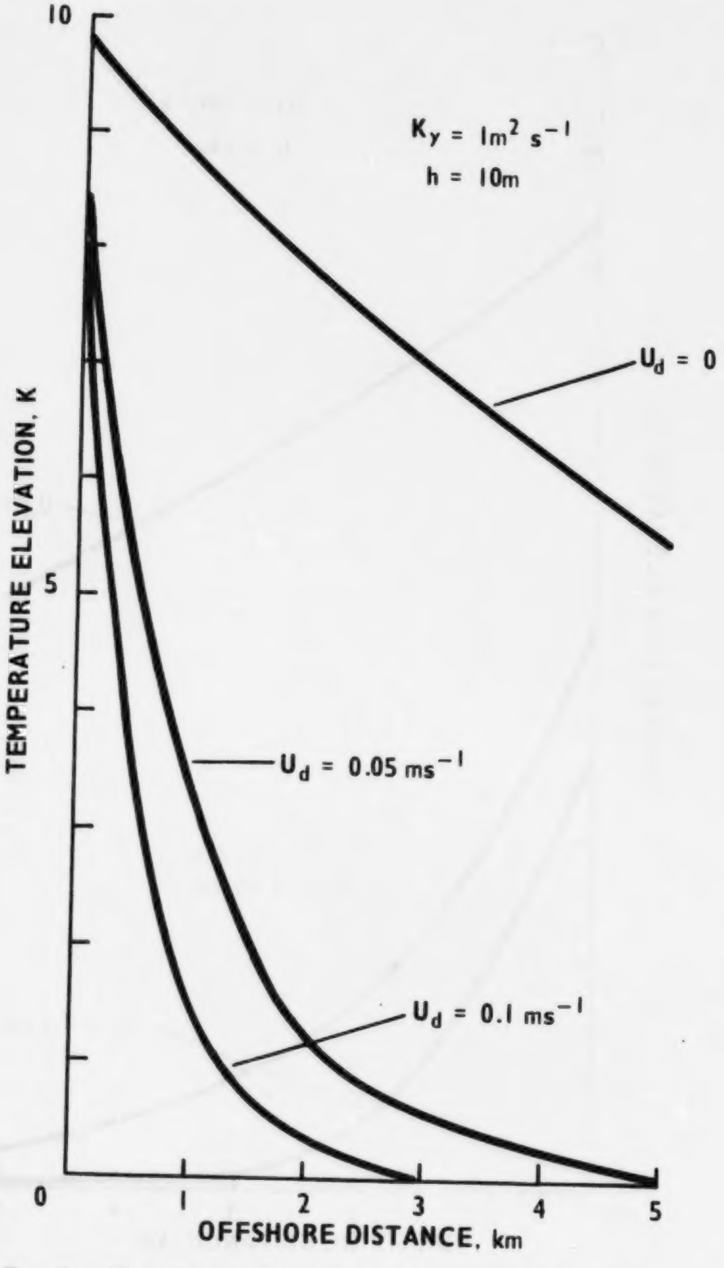

Fig. 2a Temperature Elevation Offshore from Source

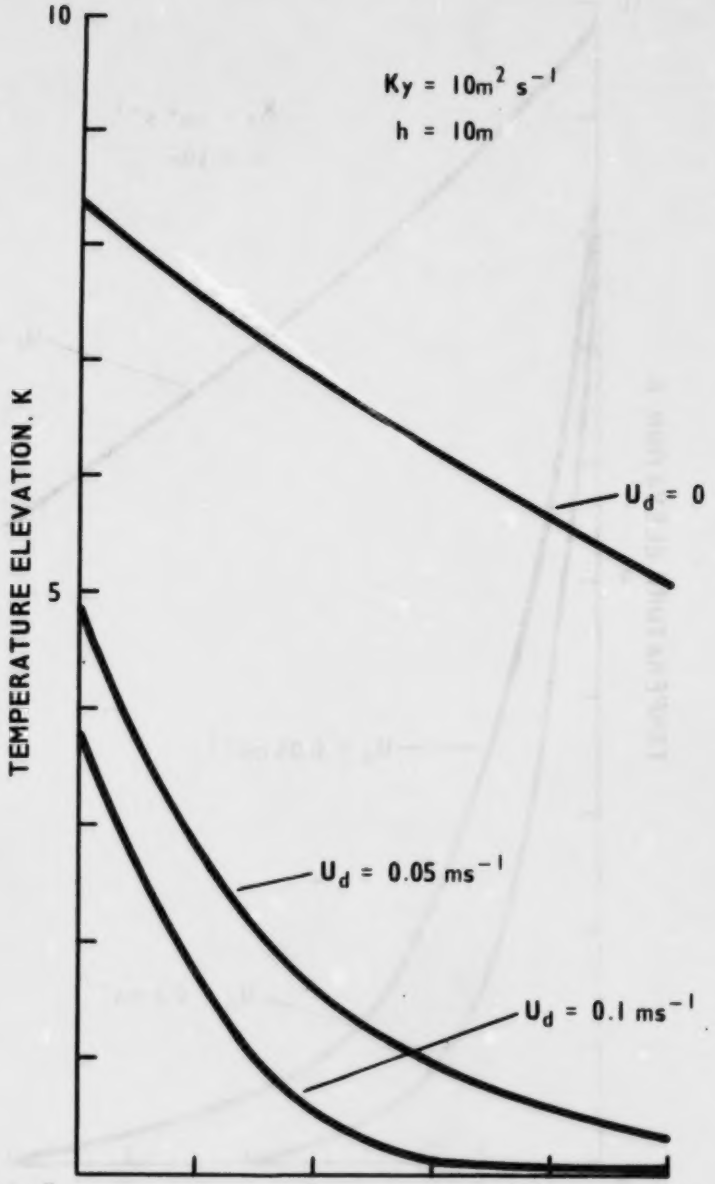

Fig. 2b Temperature Elevation Offshore from Source

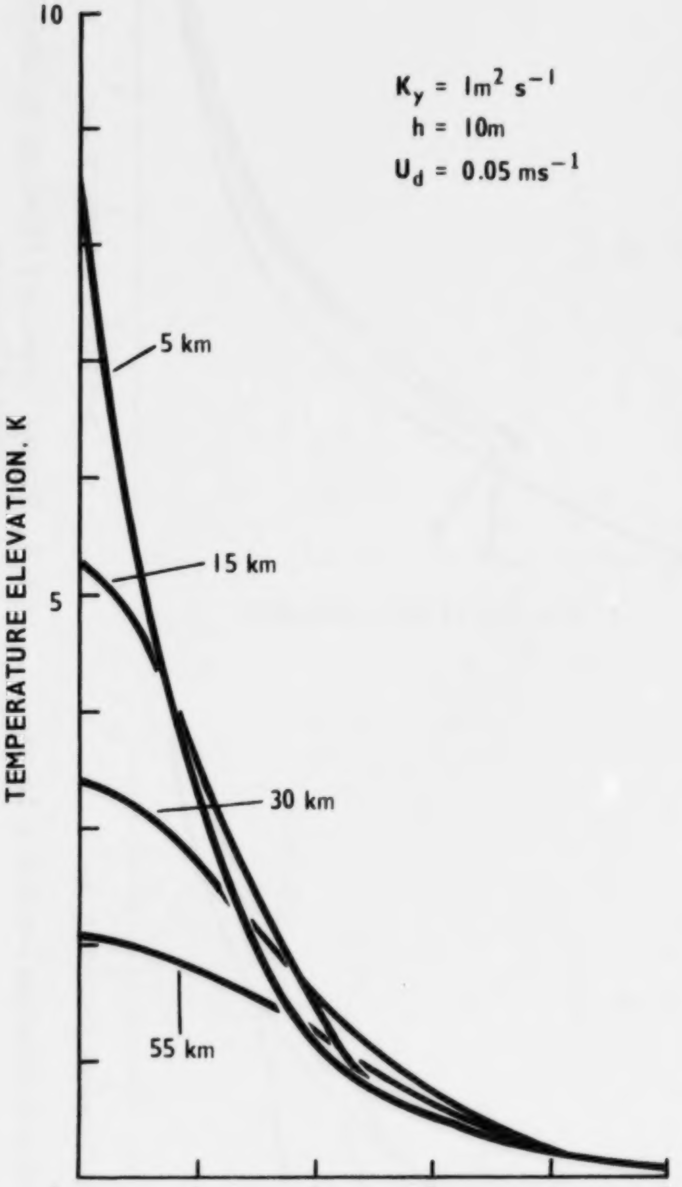

Fig. 3a Temperature Distributions Downdrift of Source

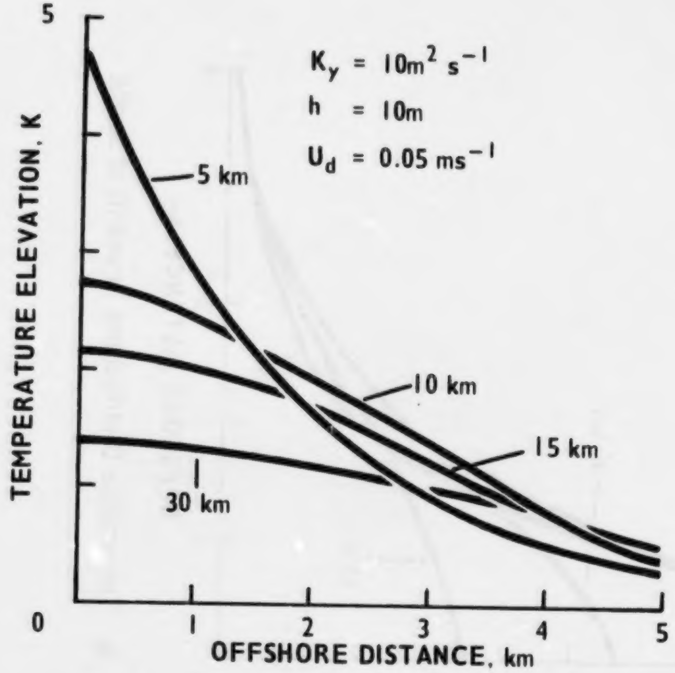

Fig. 3b Temperature Distributions Downdrift of Source

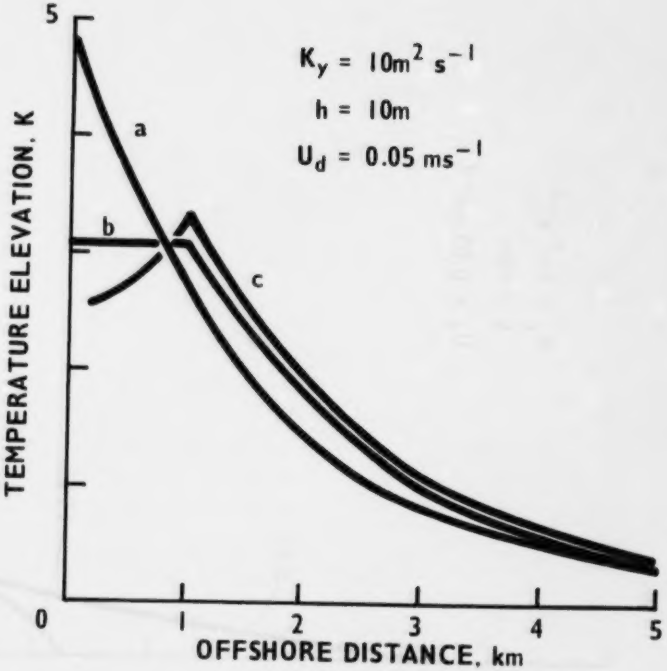

Fig. 4 Offshore Temperature Elevations for Different Locations of Discharge

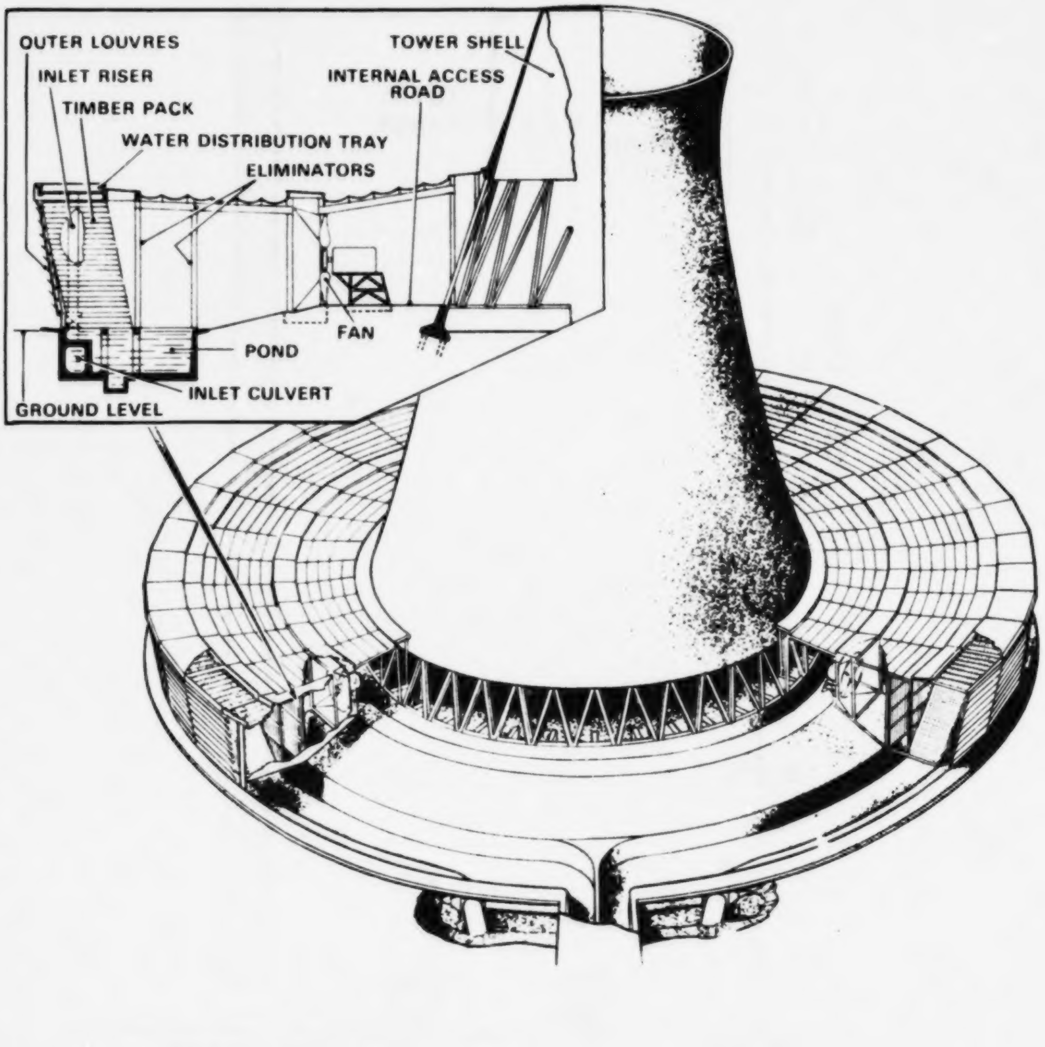
OUTER LOUVRES
INLET RISER
TIMBER PACK
WATER DISTRIBUTION TRAY
ELIMINATORS
TOWER SHELL
INTERNAL ACCESS ROAD
FAN
POND
INLET CULVERT
GROUND LEVEL

Fig. 5 Assisted Draught Cooling Tower

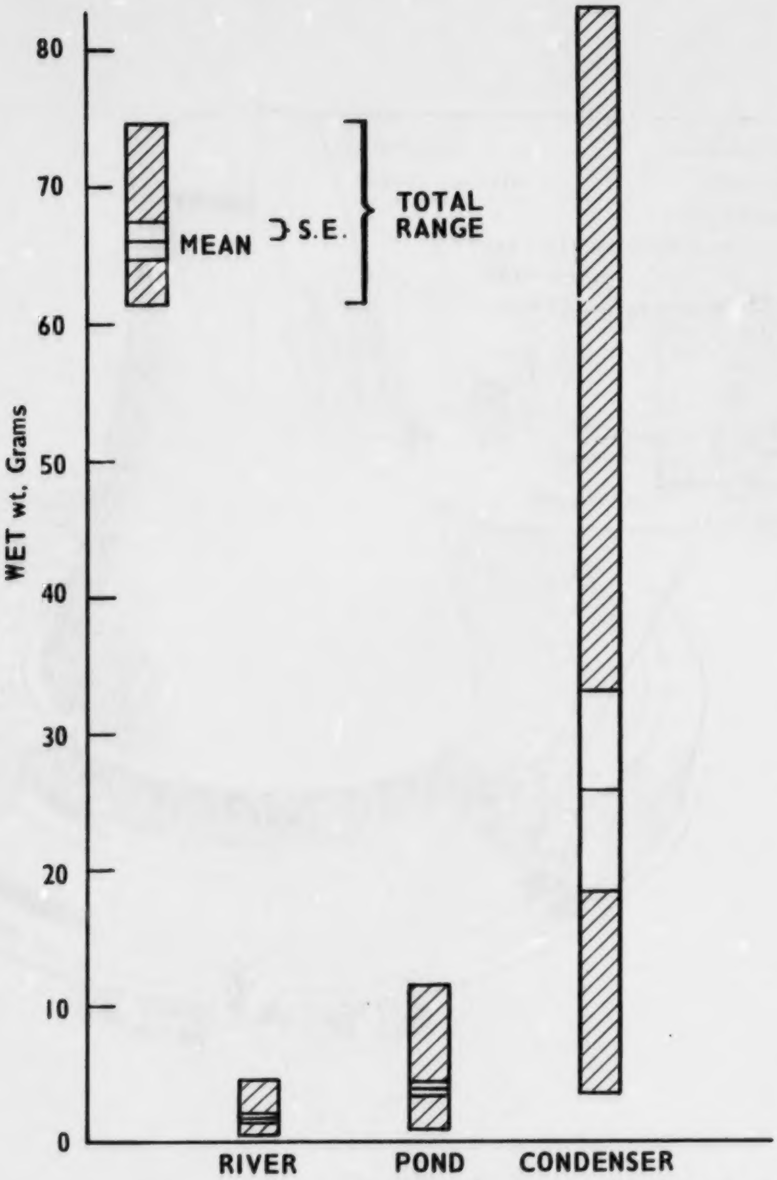

Fig. 6 Eel Weights after 12 Months in River, Pond and Condenser Water

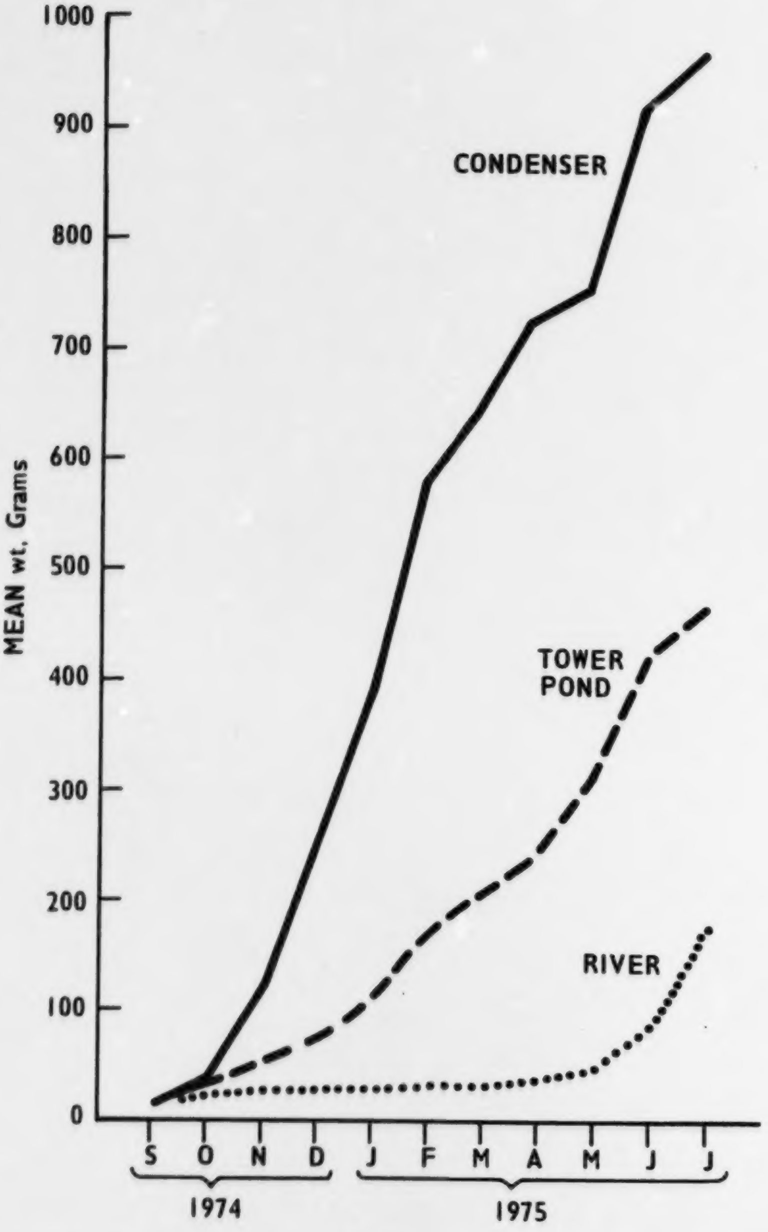

Fig. 7 Comparative Growth Rates of Carp

OMIT

VIII-C-217

THE EXCESSIVE BURDEN AND WASTE OF DUPLICATIVE REGULATION

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ABSTRACT

A case history of the experience gained while struggling to obtain authorizations from seven regulatory agencies for the operation of the Quad-Cities Nuclear Power Station. The ultimate result of original struggle was an order to close cycle the condenser cooling system. Once in operation, the ongoing limitation by these agencies and an advisary conservation organization has continued to impede the normal and economical operation of the station.

Over the period of three years review of the operational aquatic monitoring programs with these agencies has demonstrated that no adverse biological impacts were occurring, nevertheless, opposition to open cycle cooling has been continued.

Compliance with Governmental regulation and awareness of administrative policy is not a new phenomenon to the utility industry. In fact, responding has become an important part of my staff's everyday work and on occasion weekend and evening activity. It has been my experience that if a regulation, or the policy for its administration, limiting an effluent to protect the environment is based on scientific fact and a sound implementation process, it's a rational regulation with a purpose and we have no problem in the compliance process. Certainly good regulations are needed and are here to stay and our industry has been governmentally regulated for many years.

Unfortunately, this is the exception rather than the rule, and as I will point out, in some instances they have become burdensome, duplicative and wasteful for efficient power plant operation. The reason for this has been that during the past decade, the rapid creation of new statutes, policies, guidelines, and increased regulatory requirements under existing laws have resulted in a weight of regulatory duplication which hampers our performance and significantly increases electrical costs and inefficient uses of energy. This regulatory and compliance requirement atmosphere has become overwhelmingly cumbersome and we have found ourselves responding to a moving target which is composed in part of unscientifically founded regulations in a state of change. This in many instances has provided the adversary environmentalists ammunition for formulating erroneous opinions which indicate that anything industry does is environmentally obscene, even though our power plant constructional and operational activities are within the statutory framework of specific regulations. In addition, other confounding elements confronting the industry are inadequate considerations of cost versus benefits, conflicting programs, complexities of government, overlapping regulatory authority without clear definition of responsibilities, inadequate implementation provisions, duplicative and burdensome requests for information and complex legal jargon which are difficult to interpret (at least for the engineer or scientist).

The complexities of government, to cite just one example, is best illustrated by simply listing the organizations that have a hand in utility regulation and to a lesser extent with other industry. In addition to the FPC, EPA and NRC, we must comply with the requirements of the Department of Interior, FWS, DOT, Corps of Engineers, FEA, EEOC, FAA, FCC, OSHA, NLRB, SEC, Coast Guard, etc. In total, there are more than 80 Agencies who administer over 1,000 Federal Regulations. It has been said that while Presidents, Congressmen and top management of these agencies come and go, these bureaucratic organizations grind merrily along and are not directly accountable for their actions. Regulatory intrusion continues to increase and its only master seems to be the press and the courts which do an even better job of obfuscating the issues.

The recent past has been discouraging and the future does not seem too promising. For example in the past 15 years, 235 departments, bureaus, agencies and commissions were formed and only 21 were eliminated. In 1937, the Federal Register, Daily Bulletin Board of Administrative Agencies totaled 3,400 pages. By 1975, the annual paper consumption had risen to over 60,000 pages, Its volume is growing at a rate greater than the population, energy demand and even inflation.

To further complicate the process, one must consider the corresponding increases in state and local agencies whose requirements must be met. Overlapping State-Federal authority multiplies the problems. In fact, some legislation actually encourages conflicts between State and Federal Agencies. As in the case of section 401 of the FWPCA. Here State approval is required prior to the issuance of any Federal permit. This compounds what otherwise would be a simple administrative procedure.

The impacts of governmental regulation on the utility industry are far greater than most regulators imagine or will admit and the benefits to the environment or public are hard to substantiate and in some instances cannot be done.

A case history at our Quad Cities Generating Station which was originally designed for open cycle condenser cooling and later was backfitted for closed cycle will best illustrate the reason for the frustration that my utility and I feel. It sets out the following principal concerns of the present regulatory process, unscientifically founded regulations, overlapping authority, inadequate implementation schedules, ambiguous and complex language and non-existent cost benefit considerations and imposition of requirements when there is no environmental benefit to the ecosystem to be gained.

Quad Cities Generating Station, for those of you who are not acquainted, consits of two 800 MWe Megawatt Electric) boiling water reactors and is located alongside pool 14 of the Mississippi River, 25 miles north of Moline, Illinois. The Station is jointly owned by Edison and Iowa-Illinois Gas and Electric Company. Circulating water pumps withdraw about 2,270 cubic feet/sec. (CFS) (1,000,000 gpm) of Mississippi River water for condenser cooling. The condenser water discharge temperature under normal full load conditions is approximately 23°F above ambient river temperature resulting in a heat rejection of approximately 11.72 X 109 BTU/hr. The environmental setting is that of a very large river system, bordered with industry and municipal discharges upstream and several unique biological habitats that are outside of any plant influence. The River in the vicinity of the plant site is approximately 2,800 feet wide. The main river channel, through which 75-80% of the river passes is on the west side and is about 800 feet wide and 25 feet deep. The 7-day, 10-year low flow during the period 1939-1968 is 13,200. The average low flow is 46,000 and the maximum daily flow is about 237,000 cfs.

The original AEC application for Quad Cities was filed on May 31, 1966 and proposed a once-through design for condenser cooling water flow. A modification to a wingdam originally installed by the Corps of Engineers, was planned to direct the discharge into the deeper, higher velocity region of the center of the River where the biological productivity is very low. At this time, the Illinois thermal standard for discharges was a maximum river temperature of 90°F after mixing of the cooling water with the normal flow of the river. Permits to construct and operate this system had been obtained and the intake flow and discharge channel were being constructed. Work, however, on the relocated wingdam had not yet begun.

In 1969, however, Illinois amended the thermal discharge standard to limit the maximum temperature to 88°F and to require a maximum of 5°F at the edge of a mixing zone which extended 600 feet downstream of the point of discharge. A standard which had little or no technical basis.

To determine if this discharge system could meet the new thermal criteria, a thermal hydraulic model study of the river and discharge was undertaken by the University of Iowa to determine if the required mixing to meet the new standard could be achieved if the thermal effluent was directed into the main channel by means of the relocated wingdam. The results of the study demonstrated that the new thermal criteria would not always be met at the edge of the mixing zone with this type of low velocity shoreline discharge. The model further indicated that during periods of low flow the thermal standards could only be met if the condenser water discharge were completely mixed with the river flow within the mixing area. Consequently, other types of discharge structures had to be considered. After reviewing the options available to us, the number of possible open cycle discharge designs was very quickly narrowed to some type of high velocity multiport diffuser system which would assure complete discharge mixing with the river in the specified 600'. Since sufficient time was not available to adequately test, design and install the multiport diffuser system prior to the scheduled plant start up, it was necessary to develop an interim design for dissipating heat from the station. Model testing indicated that the best design for this interim period was a shoreline slot jet discharge system.

In early 1971, Edison applied to the Army Corps of Engineers requesting a permit to construct the diffuser pipe system. The Corps, however, replied that it could not issue a construction permit until the various state agencies, concerned, had given approval for the project. Since the diffuser pipe extended across the Illinois-Iowa border, the center of the river, approval was needed from three Iowa agencies as well as the Illinois Pollution Control Board. (The Iowa Pollution Control, Iowa Conservation Commission and Iowa Natural Resources Commission). (ICC and INRC were only for construction permits). The latter two agencies were really involved for obtaining construction permits.

More than two weeks of hearings before the Illinois Pollution Control Board were held in May and June of 1971. The various particpants included the Illinois Attorney General, U.S. Environmental Protection Agency, and Iowa Water Pollution Control Commission.

The Illinois Pollution Control Board decided that the diffuser discharge system would meet its new very restrictive standards and would not significantly impair Mississippi River's ecosystem. In November, it granted a permit to build the diffuser pipe system. This permit included a variance to operate the plant with a side jet until the diffuser pipe went into service.

Prior to this time, the AEC relied upon State water authorities to determine if a proposed nuclear power plant would have an adverse effect on adjacent waterways. In mid-July, after the Illinois hearings, however, the Calvert Cliffs Decision interpreted NEPA as requiring the AEC to independently evaluate all environmental aspects of new nuclear power plants including thermal effects. NEPA, totally devoid of an implementation schedule, best illustrates the effects of legislation passed without a thorough understanding of its likely impacts.

In March of 1971, the Iowa Conservation Commission had informed Edison that we would not need to obtain a permit from the Commission. On August 12, 1971, under pressure from the local Izaak Walton chapter, the Commission reversed its position.

In November of 1971, the Iowa Water Pollution Control Commission held a two day hearing in DesMoines in conjunction with the other two Iowa agencies. Although it was concluded that the diffuser system would meet all the Iowa standards for thermal discharges, an operating permit was denied. The basis was uncertainties as to the long-term effects of the cooling system on life in the Mississippi River in spite of considerable testimony to the contrary based upon several years of aquatic monitoring in the area of Quad Cities.

Independently of the struggle to obtain permission to operate the diffuser pipe, we applied to the AEC on October 12, 1971 for a license to operate at 50% of full power. The AEC agreed to consider the application, claiming that issuance of a partial power operating license did not require a revision of the original environmental impact statement. Having learned of the AEC's decision to consider issuing a 50% license, the Illinois Attorney General, the Izaak Walton League of America, and the United Auto Workers Community Action Program filed a suit in the District Court of Washington, D. C. seeking to enjoin AEC action on Quad Cities' license proposals until the AEC had fully complied with the provisions of NEPA. Following extensive testimony on the economic impact of such an injunction by Commonwealth Edison, the Court on December 13, 1971, granted it.

On December 1, the Iowa Water Pollution Control Commission denied an application for an interim permit to operate the diffuser for 27 months to determine its impact. One month later, after considerable discussion, it approved issuance of a conditional operating permit which required a closed cooling system for half of the plant. Full closed cooling would be required if, at the end of 36 months of operation, Edison could not demonstrate that there had been no damage to the environment.

On January 21, 1972, Edison then renewed its permit application with the Iowa Conservation Commission. On May 7, contrary to the recommendations of its staff biologists, the Commission refused to issue the permit citing again the uncertainties in the long-term ecological effects. They felt that total closed cooling was the only justifiable alternative.

Within three weeks, we had agreed to install a full capacity closed cooling system by May 4, 1975. As a result, the injunction prohibiting the issuance of the AEC licenses was dismissed. The estimated initial investment for the closed cooling cycle installation was over $31 million not including significant costs over the life of the plant from capability losses due to additional pumping requirement, increased turbine back pressure, and increased operating and maintenance costs. This final concession was made to get both Quad Cities Units in service for the summer of 1972. Having this new plant idle would have cost in excess of $1,000,000 a week. This loss includes the large quantities of power that would have to be produced by less efficient coal fired equipment or by more expensive oil-fueled jet peaking units. Unit 1 had been ready to load fuel since August of 1971 and Unit 2 since December of 1971

Environmental monitoring of the Mississippi River began prior to initial operation of the Station. Monitoring data has been collected and evaluated during each of the various opened and closed cycle modes of operation since start up of the first unit in April of 1972. The data has substantiated our predictions that the opened cycle operation of the plant using the diffuser pipe would have no adverse impact on the river. In fact, studies indicate that during all the open cycle operation periods, water quality criteria have been met.

In retrospect of the governmental decisions which required us to operate completely closed cycle, they have been in complete error since studies have confirmed that full closed cycle cooling is not necessary to protect the ecology of the Mississippi River. More importantly, there is no environmental benefit to be gained by having been forced to closed cycle operation. It has necessitated spending millions for initial installation costs and additional millions in operating costs over the life of the system not to mention that operation of the system is consumptive in terms of water use, energy use and creating potential terrestrial impacts than the open cycle diffuser system. The cooling canal has been shown to cripple the station with full closed cycle cooling.

The station has a design capacity, as I mentioned earlier, of 1,600,000 Kilowatts. Closed cycle operation has been found to limit this capacity to approximately, 1,000,000 kilowatts or less, about half of the time, to less than 600,000 kilowatts for the equivalent of about two months a year, and to less than 400,000 kilowatts under the most adverse hot weather conditions. In short, the spray canal simply does not have enough capacity to permit efficient station operation.

The spray canal is consumptive of river water. This use may approach 30,000 gal./min. considering evaporative losses and wind drift losses. Although drift losses for a spray system are considered to be less than in cooling towers and the drift losses are localized and occur in a relatively short distance from the source, some environmental impact is inevitable and is expected to occur as fogging and icing. Every effort has been taken to minimize this impact by keeping the greatest possible distance between the canal and roads.

The consumptive nature can be translated into replacement energy costs. It is estimated that the combined reductions are equivalent to about 15,000,000 gallons of middle distillate petroleum products not to mention replacement energy due to the losses to the system incurred in closed cycle derating.

What has been gained by having been required to operate closed cycle? Nothing. The net benefit to the public has been negative. In fact, as I've mentioned, operation has been demonstrated to be very consumptive energy of water, resources, and there are no environmental benefits to be gained by closed cycle operation since actual open cycle diffuser pipe operation has produced no detectable effect on river ecology.

The unwarranted expenditure and requirement leading to closed cycle operation is attributed to the lack of confidence in and understanding by the regulatory agencies and intervenors of what the predicted effects on river ecology from open cycle diffuser pipe would be prior to operation. Because of the uncertainties of the effects on the river ecology these groups took the most conservative stand of requiring that we commit to closed cycle by 1975 in order to get the station operational in 1972 using the open cycle diffuser pipe system.

The entire case of Quad Cities condenser cooling water system evaluation provides a classic example of the problems of the excessive burden and waste of duplicative regulation. As we reflect on how the closed cycle requirement originated, it is apparent that the emotion of the early days of 1971 have died down but nevertheless the basic concerns,I mentioned earlier, of our regulatory process still exists and our struggle to seek permission to operate the station open cycle, which would be environmentally acceptable, continues.

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NUMERICAL AND REMOTE SENSING STUDIES OF LAKE BELEWS, AN ARTIFICIAL COOLING LAKE

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ABSTRACT

Lake Belews was built in 1970 by Duke Power Company of North Carolina to dam the water flow in Belew Creek. The lake serves as a cooling reservoir for 2286 megawatt coal fired electric power plant. The study is being conducted to estimate the spread of thermal plume under the plant operating conditions and the prevailing meteorological conditions. The study is to provide information on the distribution of currents and temperatures in the Lake. The method of study includes infrared scanning of surface temperatures, measurement of vertical thermal structure from boats, measurement of velocities from a boat and simulation of the fluid dynamics and heat transfer processes in the lake by a three-dimensional, numerical, rigid-lid model. The field data is used to calibrate and verify the model. Field data is gathered in the morning to provided initial conditons. Predictions are made by the model for the afternoon of the same day. These predictions are compared with the afternoon data to calibrate and verify the model. The verified model is used to estimate the effect of bottom topography, meteorology and plant operating conditions on the currents and temperatures in the lake. The study shows that the main portion of the lake exhibits presence of a thermocline, the circulation in the main lake is dominated by wind-driven currents, and is confined in the epilimnion portion of the lake, in the mixing pond portion of the lake bottom topography influences the flow of the plant discharge and most of the cooling takes place in the main lake.

(1) INTRODUCTION

1.1 Background

Since September 1973, an interdisciplinary team from the University of Miami under NASA sponsorship has been engaged in the development of generalized, predictive three-dimensional thermal pollution mathematical models. In the initial development of the model, two Florida Power and Light power plant sites were selected for validation. The Cutler Ridge fossil full plant on Biscayne Bay provided a good example of a shallow lagoon type site while the St. Lucie nuclear power plant being constructed on Hutchinson Island, Florida provided an open ocean-site. These two geographically contrasting sites were selected to demonstrate the flexibility of the model.

In discussions with potential user agencies, it was agreed that an inland man-made reservoir receiving a power plant discharge would afford an important model application. Duke Power Company in Charlotte, North Carolina was contracted concerning the possibility of using one its cooling lakes as a validation site. Duke suggested that Belews Lake, North Carolina would be suitable application for validating the model. This site is representative of a small flow through lower piedmont man-made cooling pond and provides a significantly different application for the model.

1.2 Site Location - Physical Description

Belews Lake is located in North Carolina, approximately 26 kilometers (16 miles) north-east of Winston-Salem. The lake was formed by constructing a dam across Belews Creek 1.2 kilometers (0.75 miles) above the confluence with the Dan River. Duke Power Company built the lake to serve as a cooling pond for a steam generating power plant.

At full pond elevation of 219.5 meters (720 feet) above mean sea level (amsl), Belews Lake has a surface area of 15.6 km^2 (3863 acres), a volume of 0.2km^3 (167,124 acre-feet), a maximum depth of 38.2 meters (125.3 feet) with an average depth of 13.2 meters (43.3 feet). The total watershed area is approximately 204.6 km^2 (79 mi^2) which yields an average annual flow of approximately 2.5 m^3/sec (90 ft^3/sec). This results in a theoretical retention time of 2.5 years. The lake is divided into a Mixing Pond and a Main Lake, Fig. 1. The Mixing Pond was formed by a dam built across West Belews Creek. At full pond, it has a surface area of 1.7 km^2 (420 acres) and a maximum depth of 13.7 meters (45 feet). The two water bodies are connected by a 9.1 meter (30 feet) wide, 1.3 kilometer (0.8 mile) long and 7.62 meters (25 feet) deep canal. Belews Creek Steam Station is a coal fired steam generating station built by Duke Power Company at Belews Lake. It consists of two independent generating units each rated at 1143 megawatts electrical (MWe) for a total capacity of 2286 MWe.

Units 1 and 2 began commercial operation in 1974 and 1975, respectively. Condenser cooling water (CCW) requirements per unit range from 32.7 m^3/sec (115 ft^3/sec) in the summer to 21.5 m^3/sec (760 ft^3/sec) in the winter. At full load, the corresponding summer and winter CCW temperature rises are 10°C (18°F) and 15°C (27°F), respectively. Full load thermal efficiency for the plant is approximately 40%.

Belews Creek Steam Station utilizes a once through cooling cycle. The plant withdraws condenser cooling water from a surface intake in the Main Lake and discharges to the Mixing Pond. Initial cooling occurs due to mixing and surface heat transfer. The Mixing Pond discharges to the Main Lake through a discharge canal. The pre-cooled discharge plume spreads over the Main Lake surface releasing its stored heat to the atmosphere through evaporation, radiation and convection.

Extensive field measurements have been made on Belews Lake by Duke Power Company since 1974 when the first unit went into operation. Examination of this data indicates there is essentially no thermal stratification in the Mixing Pond due to mixing induced by the plant discharge. The Main Lake, conversely, exhibits severe stratification in the summer with the thermocline forming at a depth of approximately 7.6 meters (25 feet). During the warm summer months with the plant operating at full load, the Mixing Pond temperatures may reach 37.5°C (99.5°F). Surface temperatures in the Main Lake drop to 30°C (86°F) near the intake, with bottom temperatures near 10°C (50°F). The strong stratification and low bottom temperatures in the Main Lake indicate a large majority of the plant rejected heat entering the Main Lake remains in the surface layer where it can readily be dissipated to the atmosphere.

(2) VALIDATION DATA COLLECTION PROCEDURE

2.1 Thermal Infra-Red Data

Lake surface temperatures are remotely sensed by a Daedalus multispectral scanner with an 8-14 micron thermal infra-red channel. The thermal scanner is carried aboard the NASA-6 Beechcraft C-45H aircraft owned by National Aeronautical and Space Administration at Kennedy Space Center (NASA/KSC). Flight lines are conducted over the target area and the analog scanner readout is recorded on magnetic tape aboard the aircraft.

The total extent of Lake Belews is covered by six flight lines (Fig.1). The aircraft is flown at a 609.6 meter (2000 feet) altitude, providing a scanned width of 932.7 meters (3060 feet). Resolution at this altitide is satisfactory. Data flights are typically conducted at 9:00AM and 3:00PM on a given day for validation purposes at this site.

2.2 Ground Truth Data

Simultaneous with the infra-red scanning, surface water temperatures are monitored from two boats. One is located at the north end of the lake near the impoundment and the other is at the south end in the Mixing Pond. Surface temperatures are monitored using both thermocouples and thermometers held approximately 2 inches below the water surface. A barnes PRT-5 instrument provided by NASA/KSC was also used to measure surface "skin" temperature. This instrument determines surface temperatures by measuring surface radiation. These ground truth measurements provide a means of correcting the infra-red temperature data for atmospheric attenuation.

Temperature and current velocity profile measurements are made from boats at 2 meter intervals utilizing thermocouples and an Endeco-Type 110 Remote Reading Current Meter respectively. These measurements help characterize temperature distribution and flow patterns in the lake for the day of the infra-red scanning. Hourly temperature data (surface and profile) from seven Duke Power Company continuous monitoring stations throughout the lake help characterize the lake several days prior to and during the IR scanning.

Hourly meteorological data and power plant operating data are provided for use in the model. This includes dry bulb temperature, dew point temperature, wind speed and direction, solar radiation, plant condenser flow and plant condenser temperature rise. Meteorological data is monitored continuously from a pier off an island in the middle of the lake.

2.3 May 19, 1976 Data Acquisition

IR data scans of the entire lake were successfully performed for both the morning and afternoon of May 19, 1976. Both sets of data were flown at 6096 meters (2000 feet) altitude. The thermal IR scanning window was set at 20°C - 30°C (68°F-86°F) for the morning flight and 21.1°C - 31.1°C (70°F - 88°F) for the flight in the afternoon. Corrected morning and afternoon thermal IR data is presented, respectively in Figures 2 and 3.

Field measured temperature profiles collected on May 19th for stations 5 and 6 (See Figure 2) are presented in Figure 4. Measured current velocities in the Mixing Pond at a depth of 1.5 meters (5 feet) are presented in Figure 5.

2.4 Other Thermal IR Scanning Studies

Thermal IR scanning by NASA/KSC and ground truth current and temperature measurements by Duke Power Company were conducted in August and October, 1976 and January, 1977. These studies were similar in scope to the May study. This data is presently being analyzed.

(3) FORMULATION OF MATHEMATICAL MODEL

3.1 The Mathematical Model

The model applied to the Lake Belews attempts at solving for the variables u (velocity in x-direction), v (velocity in y-direction), w (velocity in z-direction), p (pressure), T (temperature) and ρ (density). To solve for these six quantities, six governing partial differential equations are used. These governing equations are the continuity equation, three Navier-Stokes equations of the conservation of x, y, and z-momentum, the equation of state and the energy equation. Assumptions of incompressibility, hydrostatic pressure distribution, Boussinesq approximation and rigid-lid flow behavior are made to simplify the governing equations. The equations are further transformed into a stretched z-coordinate system by using the transformation

$$\sigma = \frac{z}{h(x,y)}$$

where h(x,y) is the depth of the lake and σ is the transformed coordinate. The transformation provides a rectangular domain in the vertical sections. Finite difference techniques are used to solve the governing partial differential equations. The rigid-lid model that is used for computations is discussed in detail by Sengupta, et al. (1974) and its application to Biscayne Bay is presented by Veziroglu, et al. (1974, 1975).

Various features of the mathematical model are as follows. The model is three dimensional. It predicts three dimensional fields for velocity and temperature. The model is non-linear in that it retains non-linear terms in the Navier-Stokes equations. The model is baroclinic in that the density of the of the fluid is specified as a function of temperature. The model is time dependent. It starts with specified initial conditions and thenceforth propagates solution in time. The model is applicable to water bodies with irregular horizontal boundary and bottom topography. The driving mechanisms for circulation are the wind which is specified as surface shear stress and the efflux of heat and mass. Surface heat transfer coefficient is specified based on meteorology to allow for heat exchange with the atmosphere.

3.2 Application of Model to Lake Belews

For convenience in model application, the total path of water circulation is divided into two regions, namely the Mixing Pond and the Main Lake. These two regions are treated as disconnected regions. The Mixing Pond receives hot water from the power plant, mixes it with cooler water and then discharges it into the Main Lake through the connecting canal. The Main Lake receives hot discharge from the connecting canal, cools it and from there it goes into the power plant condensers.

The primary difference in the parameters in the Mixing Pond and the Main Lake is the fact that the Mixing Pond is well mixed while the Main Lake shows thermal stratification. This in turn means that vertical eddy diffusivity in the Mixing Pond is constant over the entire depth whereas in the Main Lake vertical diffusivity decreases with depth. Variation of thermal diffusivity is defined as a function of the slope of the temperature profile and the gradient of the horizontal velocity with depth. Further discussion on this aspect is given by Sundaram et al (1972).

For computations, the entire stretch of the Mixing Pond is covered with a mesh of twenty nine lines in the x-direction by thirteen lines in the y-direction and by six lines in the stretched z-direction, Fig. 6. Stretched z-direction is a normalized coordinate in which depth everywhere in the domain varies from zero to one. Further discussion on stretching is given by Sengupta et al (   ). A two dimensional matrix of numbers defines the location of nodes of the grid as to whether they are outside, on the boundary or inside of the domain of interest. On the boundary, differentiation is made with regard to x-boundary, y-boundary, and type of corner to apply appropriate finite difference technique. The grid lines in the Mixing Pond are spaced every 60 meters in the horizontal plane and every 0.5 to 2.8 meters in the vertical direction. The computational grid for the Main Lake is also twenty nine by thirteen by six, Fig. 6. The grid lines in the Main Lake are spaced every 240 meters in the horizontal plane and every 1.0 to 7.6 meters in the normalized vertical direction.

(4) VERIFICATION FOR MAY 19, 1976

4.1 Data Base

The Mixing Pond is well mixed and does not show significant temperature stratification in the vertical direction. In the Main Lake, the temperature varies from 22.3°C at the surface to 11.0°C below 20 meters. Thermocline in the Main Lake exists at approximately 10 meters depth, Fig. 4.

Infrared mapping of the Lake Belews shows that thermal startification in the horizontal direction is much more dominant in the morning, Fig. 2. In the afternoon, stratification in the horizontal direction is reduced because of mixing from wind of 4.87 meters/sec. (10.9 mph) to 7.47 meters/sec. (16.7 mph), Fig. 3. Infrared mapping also shows that the lake is cooler in the afternoon than in the morning. It is clear from infrared data, that in the morning the plume extends towards the plant intake, Fig. 2.

The discharge temperature from unit one decreases from 25.7°C (78.3°F) at 9:00 AM to 22.5°C (72.5°F) at 3:00 PM. The discharge temperature from unit two decreases from 33.1°C (91.5°F) at the 9:00 AM to 32.9°C (91.3°F) at 3:00 PM. The average discharge temperature decreased from 29.5°C (85.1°F) at 9:00 AM to 27.9°C (82.2°F) at 3:00 PM. The mass flow rate of the discharge remains approximately at 191 x 10^6 kilograms per hours.

Velocity distribution data gathered from the boat in the Mixing Pond does not present a complete picture of the circulation in the Mixing Pond, Fig. 5. The initial circulation in the Mixing Pond is set up by imposing wind stresses and plant discharge from 6:00 AM until 9:00 AM. Temperature field in this period is set constant, thus eliminating buoyancy effects. Surface heat transfer coefficient is set at zero during this period. The isotherms plotted from 9:00 AM infrared mapping are used to specify the initial surface temperatures, Fig. 6. Temperatures below the surface are computed by specifying a constant temperature gradient of 0.05 C/meter, thus assuming 1°C temperature difference in twenty meters depth.

Because of the limitation of computer core size, the entire depth of the Main Lake is represented by six grid points. At maximum depth of 38.2 meters (125.3 feet), the grid step size in the vertical direction is 7.64 meters (25.06 feet). The depth of the thermocline is 10 meters (32.8 feet). All short time thermal activities are limited to the upper one third of the epilimnion. Thus a grid step size of 7.64 meters would not be capable of analyzing the short term physical processes in the epilimnion. It was decided to apply the model to the top 9.14 meters (30 feet) of the Main Lake. The Main Lake is treated as a constant depth basin of 9.14 meters (30 feet) depth. No slip velocity boundary condition is applied at the bottom of this basin. Also, no heat flux thermal boundary condition is applied at the bottom of this basin. Vertical eddy viscosity and vertical eddy diffusivity is kept constant at 10 cm^2/sec. The morning infrared surface temperatures are used to specify initial temperature field at the surface. The initial temperature at the bottom of the basin is set equal to a constant temperature obtained from the vertical temperature profile plotted in Fig. 4. Initial temperatures at intermediate grid points are computed by assuming linear temperature distribution from the surface of the basin to the bottom of the basin.

Wind stress on the water surface, surface heat transfer, coefficient, equilibrium temperature, plant discharge flow rate and plant discharge temperature are varied every hour from 9:00 AM until 3:00 PM. Surface isotherms at 3:00 PM, as computed from mathematical model, are compared with isotherms obtained from infrared mapping,Figs,11 & 12 Table 1 presents hourly values of air temperature, equilibrium temperature, discharge temperature, discharge flow rate, wind speed and wind direction.

4.2 Discussion of Results

1. Surface velocity distribution in the Mixing Pond is presented in Fig. 7. The velocity distribution predicted by computer model compares in magnitude and direction to the field measurements presented in Fig. 5. The velocity distribution shown in Fig. 7 was arrived at by reducing the surface shear stresses suggested by Wilson (1960) by a factor of 2.5. Surface currents are completely dominated by wind.

2. Velocity distribution at eight meters depth is presented in Fig. 8. North of the canal, flow is dominated by the plant discharge. South of the canal the circulation is dominated by wind currents. The currents at this depth are in reverse direction from those on the surface. The separation of two circulation regions is caused by the presence of an island and an embankment both of which are submerged at full pond elevation of 220.98 meters (725 feet) AMSL, just south of the canal.

3. Fig. 9 presents current distribution at a vertical cross section along the length of the Mixing Pond. It shows two distinct circulation regions. North of the submerged ridge, the currents are dominated by the discharge except at the surface. South of the submerged ridge, currents are dominated by wind circulation. Some discharge water does flow into the southern region over the submerged ridge. Vertical scale in this figure is magnified over the horizontal scale by a factor of fifteen.

SKM

4. In the Mixing Pond, the comparison of isotherms obtained by thermal infrared scanning in the afternoon with isotherms obtained by IR scanning in the morning shows three dominant effects, Fig. 10. There is a pocket of cooler water near the discharge area. This cool water was discharged from 11:00 AM until 2:00 PM from the electric power plant. Second, in the neighborhood of the canal, water temperature has dropped down from a maximum of 29.35°C to a maximum of slightly above 28.24°C. Third, south of the canal, the isotherm of 27.68°C has diffused southwards. The comparison of afternoon isotherms predicted by the model with the isotherms obtain by thermal infrared scanning shows that the first and the third effects discussed above are very well predicted. The comparison is presented in Fig. 11. Solid lines represent isotherms obtained by infrared scanning. The dotted lines represent isotherms obtained from computer model. The isotherms of 27.68°C show a very good agreement. This shows that the computer model is a good indicator of the convective processes. Also the isotherms of 27.68°C show a good agreement, thus proving that the model is a good indicator of the diffusive processes. Across from the canal, the mathematical model shows the temperatures to be 0.26°C (0.5°F) higher than the infrared temperatures. The author believes this to be a good enough agreement considering the possible errors in the field measurements and in the interpretation of infrared data.

5. Fig. 12 presents the isotherms predicted by the mathematical model for 3:00 PM (EDT) on May 19, 1976 in the Main Lake. These isotherms are plotted in dotted lines. The morning infra red measured isotherms are plotted in the same figure as chain-lines and the afternoon infra red measured isotherms as solid-lines. The comparison of afternoon infra red isotherms with the morning infra red isotherms shows that the lake is cooler in the afternoon than in the morning. The isotherms plotted from the results of mathematical model predict the same trend qualitatively. Quantitatively the isotherms of 28.2°C, 26.7°C and 25.2°C show very good agreement. The comparison between isotherms of 23.8°C and 22.3°C could be improved by adjusting the values for horizontal turbulent diffusivity and surface wind stress.

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TABLE 1. HOURLY VARIATION OF PARAMETERS ON MAY 19, 1976 AT LAKE BELEWS SITE

HOUR	T_a	W	θ	ϕ_{sn}	K	T_e	Q_1	Q_2	Q	V_i	T_{1d}	T_{2d}	Td
6	—	4.02	220	—	—	—	92.93	98.39	191.32	9.263	24.94	33.11	29.14
7	—	4.25	255	—	—	—	93.31	98.42	191.68	9.281	24.94	32.94	29.05
8	—	3.98	255	—	—	—	93.06	98.34	191.40	9.287	25.06	32.94	29.11
9	12.28	4.87	255	60.22	5.64	25.17	93.25	98.42	191.67	9.280	25.72	33.06	29.49
10	14.06	6.35	250	63.31	6.63	25.39	93.06	97.88	190.94	9.245	26.28	33.06	29.75
11	15.56	6.84	255	65.07	6.92	26.61	95.95	97.94	190.88	9.242	25.83	29.28	27.60
12	17.28	7.47	280	62.12	7.22	26.67	92.80	97.97	190.77	9.236	24.94	30.72	27.91
13	18.22	7.06	285	61.74	7.43	27.56	92.57	97.71	190.41	9.219	24.28	30.44	27.41
14	19.11	6.35	280	60.35	7.55	28.56	92.59	97.81	190.39	9.218	23.11	30.78	27.05
15	20.00	6.57	285	57.00	7.71	28.61	92.51	98.10	190.60	9.228	22.50	32.94	27.88

T_a = Air temperature in ^oC
W = Wind velocity in meters/sec.
θ = Wind direction in degrees
ϕ_{sn} = Incident solar radiation in calories/cm^2 hr.
K = Surface heat transfer coefficient in calories/cm^2. ^oC. hr.
T_e = Equilibrium temperature in ^oC
Q_1 = Unit one discharge in kilograms/hour (X 10^6)
Q_2 = Unit two discharge in kilograms/hour (X 10^6)
Q = Total plant discharge in kg/hr (X 10^6)
V_i = Imposed inlet velocity in cm/sec.
T_{1d} = Unit one discharge temperature in ^oC
T_{2d} = Unit two discharge temperature in ^oC
T_d = Average discharge temperature in ^oC

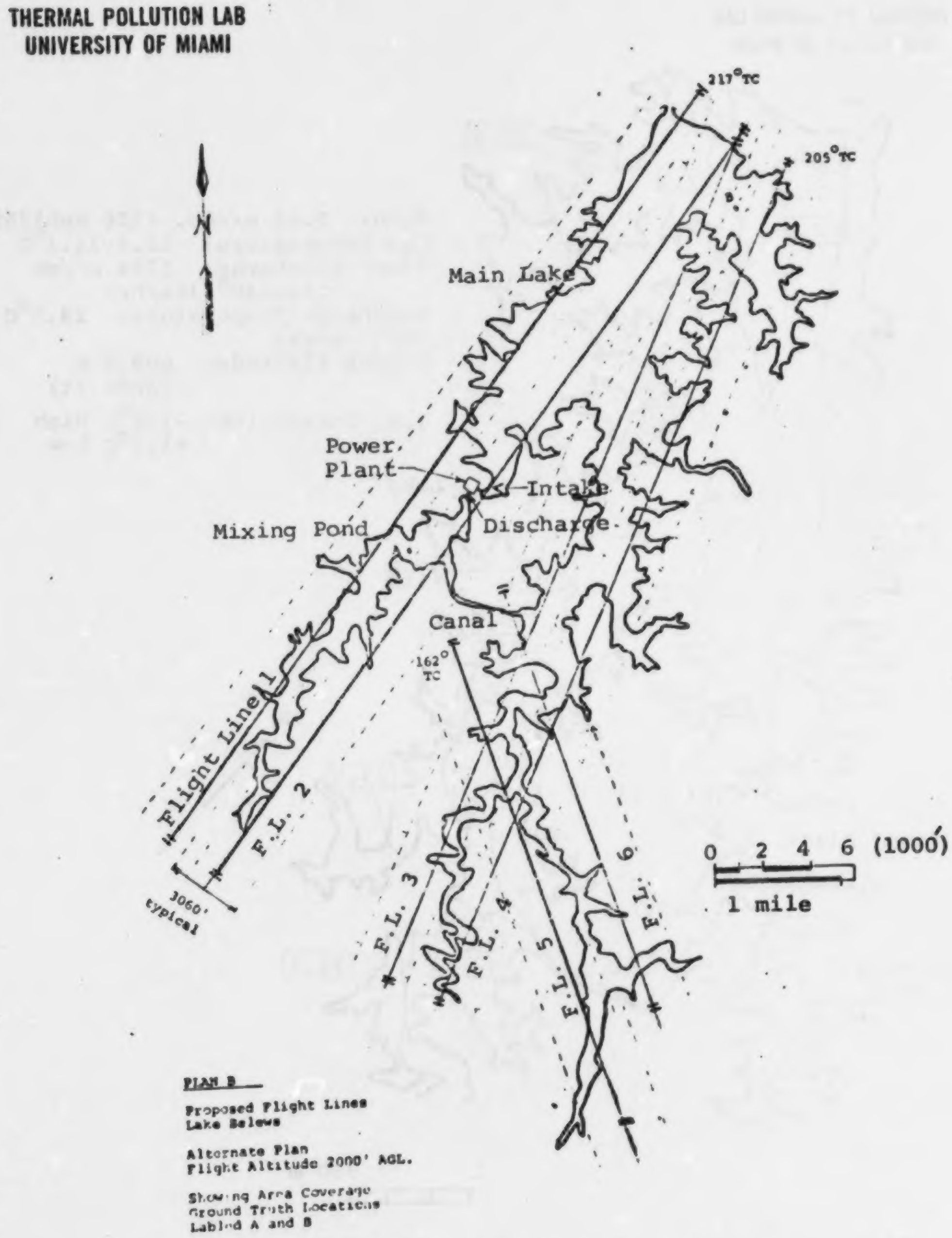
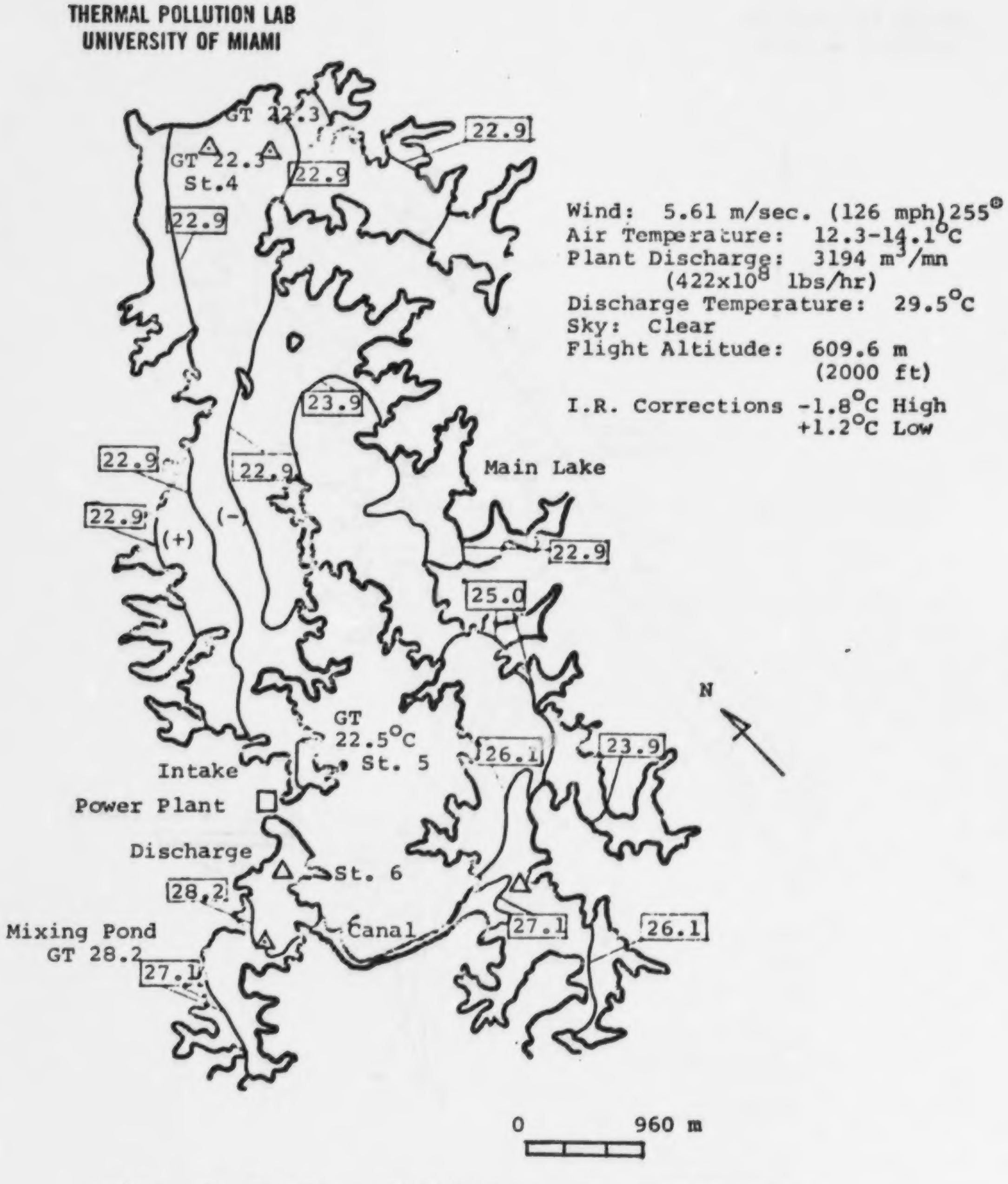

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI
N
217°TC
205°TC
Main Lake
Power Plant
Intake
Discharge
Mixing Pond
Canal
162° TC
Flight Line 1
F.L. 2
F.L. 3
F.L. 4
F.L. 5
F.L. 6
3060' typical
0 2 4 6 (1000')
1 mile
PLAN B
Proposed Flight Lines
Lake Belews
Alternate Plan
Flight Altitude 2000' AGL.
Showing Area Coverage
Ground Truth Locations
Labled A and B

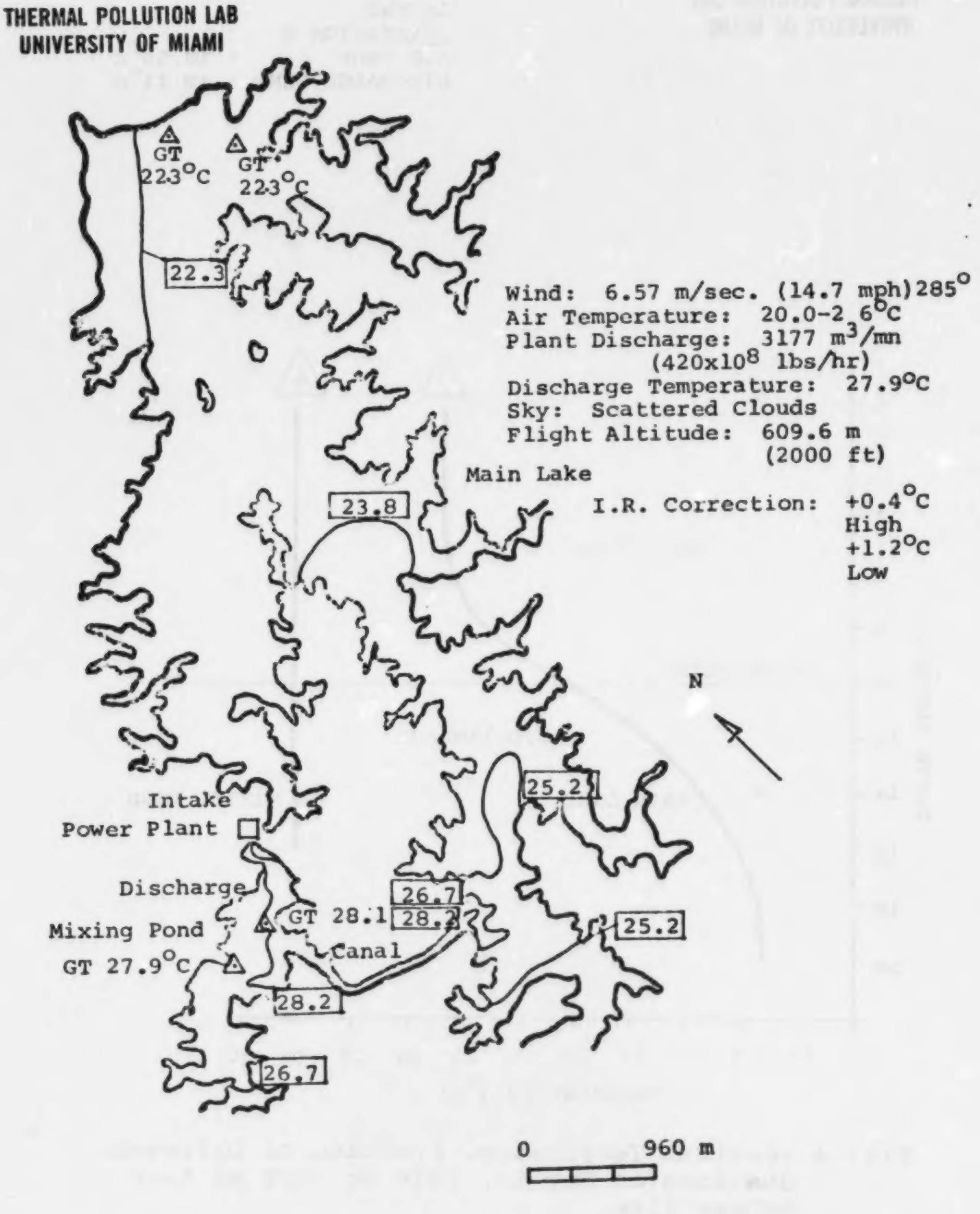
Fig.1 Flight Paths of NASA-6 Aircraft At Lake Belews, North Carolina, 19 May 1976


THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI
GT 22.3
GT 22.3
St.4
22.9
22.9
22.9
23.9
22.9
22.9
22.9
(+)
(-)
Main Lake
22.9
25.0
GT
22.5°C
St. 5
26.1
23.9
N
Intake
Power Plant
Discharge
St. 6
28.2
Mixing Pond
GT 28.2
Canal
27.1
26.1
27.1
0
960 m

Wind: 5.61 m/sec. (126 mph)255°
Air Temperature: 12.3-14.1°C
Plant Discharge: 3194 m^3/mn
(422x10^8 lbs/hr)
Discharge Temperature: 29.5°C
Sky: Clear
Flight Altitude: 609.6 m
(2000 ft)
I.R. Corrections -1.8°C High
+1.2°C Low

Fig. 2 Surface Temperatures by I.R. Remote Sensing on May 19, 1976 at Lake Belews Site. Time 0905-0955 EDT

SKM


THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI
GT
22.3°C
GT
22.3°C
22.3
Main Lake
23.8
N
25.2
Intake
Power Plant
Discharge
Mixing Pond
GT 27.9°C
GT 28.1
26.7
28.2
Canal
25.2
28.2
26.7
0
960 m

Wind: 6.57 m/sec. (14.7 mph)285°
Air Temperature: 20.0-26°C
Plant Discharge: 3177 m^3/mn
(420x10^8 lbs/hr)
Discharge Temperature: 27.9°C
Sky: Scattered Clouds
Flight Altitude: 609.6 m
(2000 ft)

I.R. Correction: +0.4°C
High
+1.2°C
Low

Fig. 3 Surface Temperatures by I.R. Remote Sensing on May 19, 1976 at Lake Belews Site. Time: 1513-1549 EDT

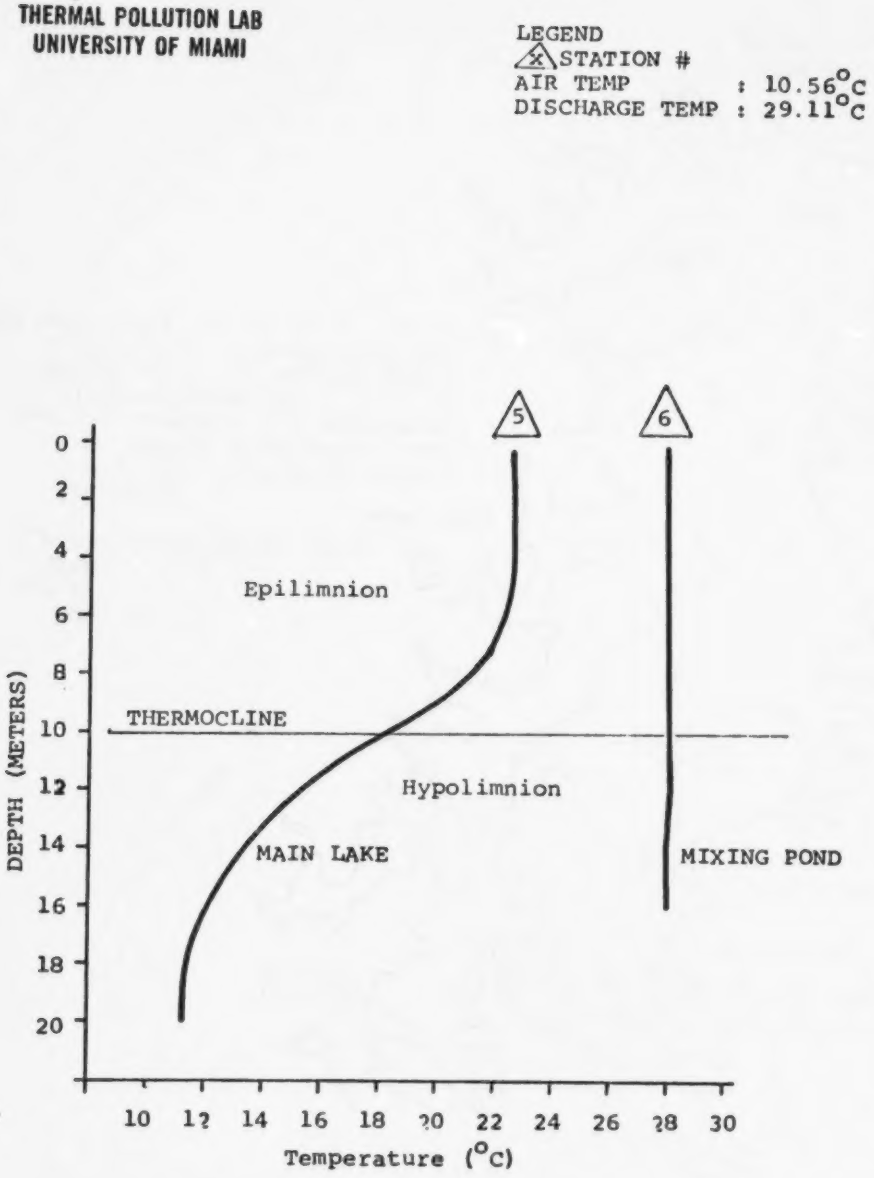


Fig. 4 Vertical Temperature Profiles At Different Stations on May 19, 1976 At 8EDT At Lake Belews Site

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

TIME : 9-15 EDT
WIND : 4.87-6.57m/sec
(10.9-14.7 mph)
255-285°
PLANT DISCHARGE : 191×10^6 kg/hr

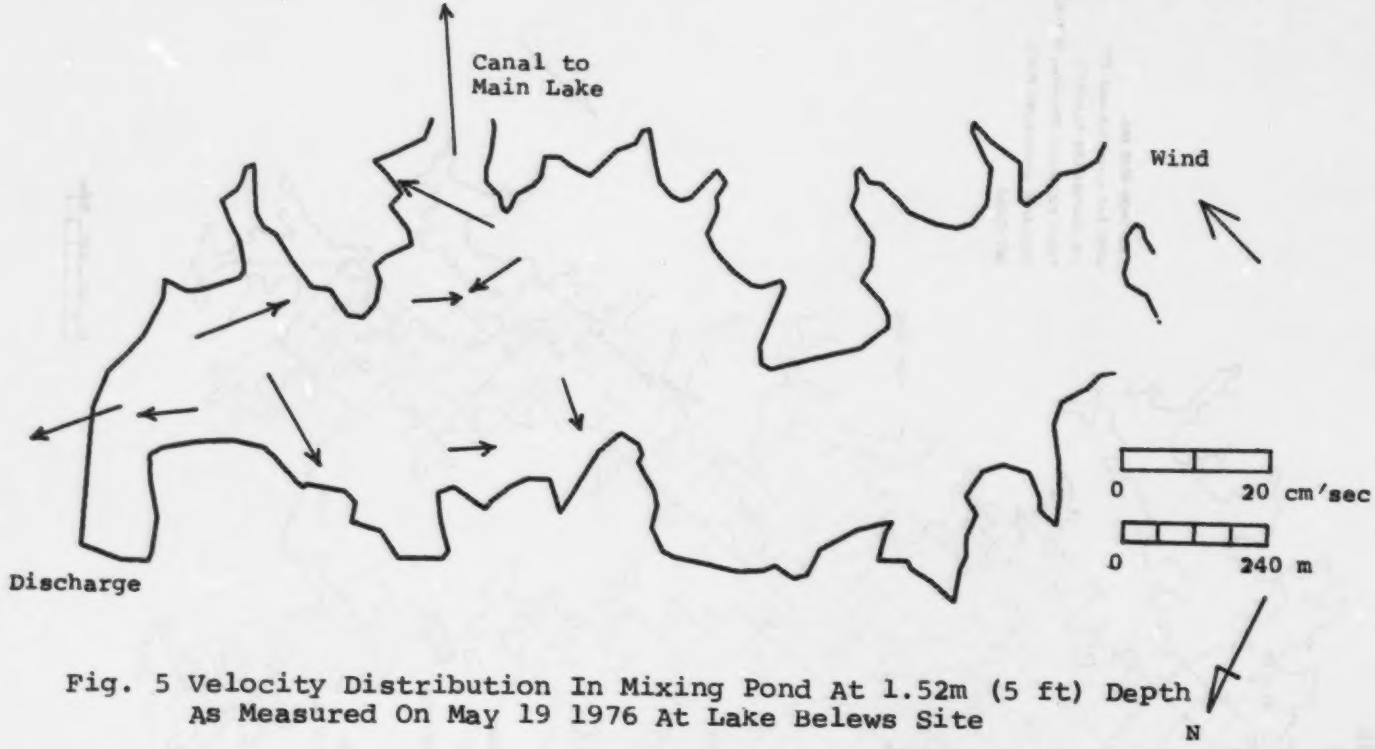

Canal to
Main Lake
Wind
0
20 cm/sec
0
240 m
N
Discharge

Fig. 5 Velocity Distribution In Mixing Pond At 1.52m (5 ft) Depth
As Measured On May 19 1976 At Lake Belews Site

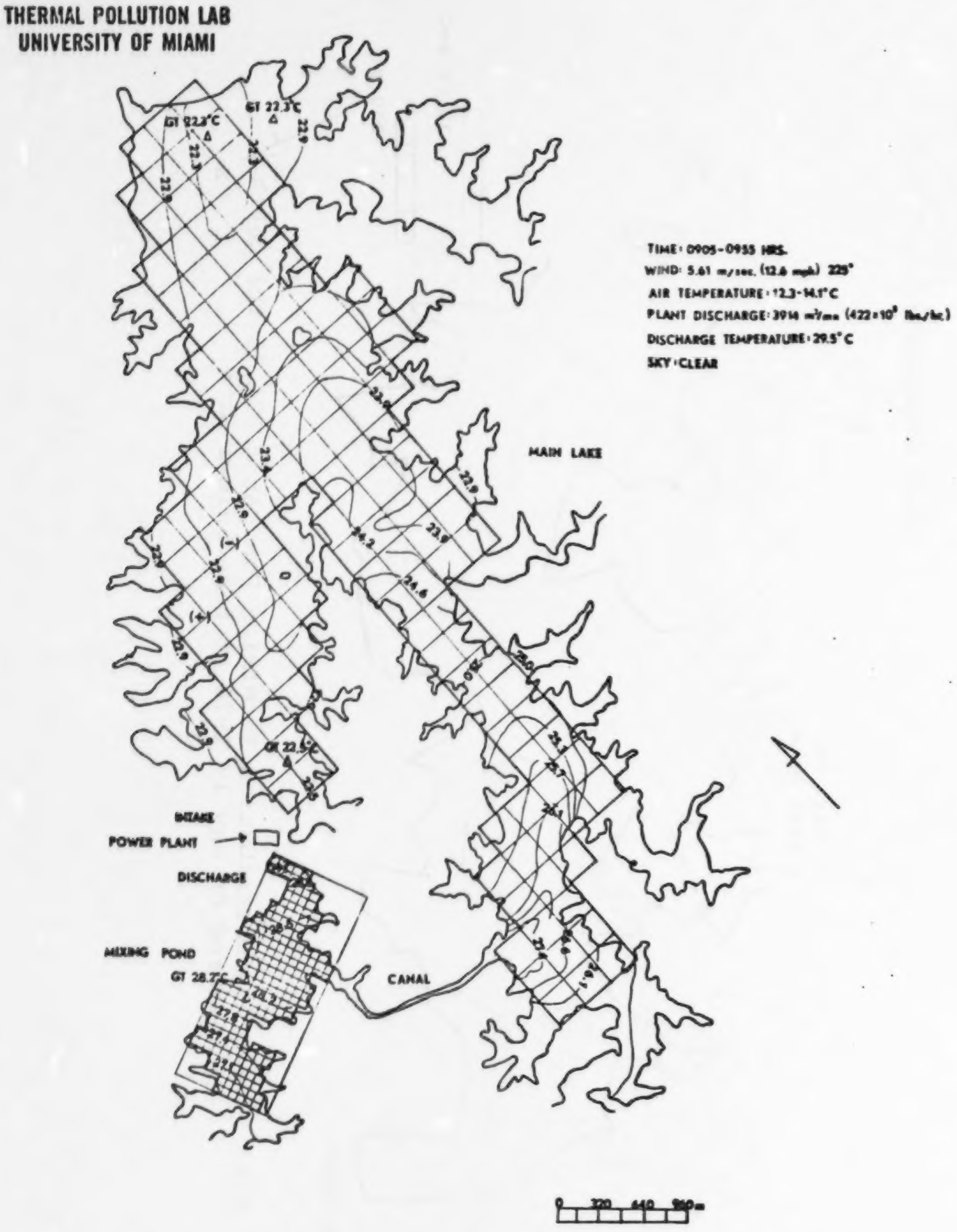

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI
TIME: 0905-0955 HRS.
WIND: 5.61 m/sec. (12.6 mph) 225°
AIR TEMPERATURE: 12.3-14.1°C
PLANT DISCHARGE: 3914 m³/min (422×10⁶ lbs/hr.)
DISCHARGE TEMPERATURE: 29.5°C
SKY: CLEAR
GT 22.3°C
GT 22.3°C
MAIN LAKE
GT 22.5°C
INTAKE
POWER PLANT
DISCHARGE
MIXING POND
GT 28.2°C
CANAL
0 320 640 960 m

Fig. 6 Interpolation Of Surface Temperatures From Surface Isotherms Obtained By I.R. Remote Sensing On May 19, 1976 At Lake Belews Site

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

Δt : 36 sec
Time : 1500 EDT
Wind :6.4 m/sec (14.2 mph)W
Plant Discharge :190×10^6 kg/hr
Horizontal Diffusivity :15,000 cm^2/sec
Vertical Diffusivity :10 cm^2/sec
Air Temperature :19.1°C
Discharge Velocity :9.218 cm/sec

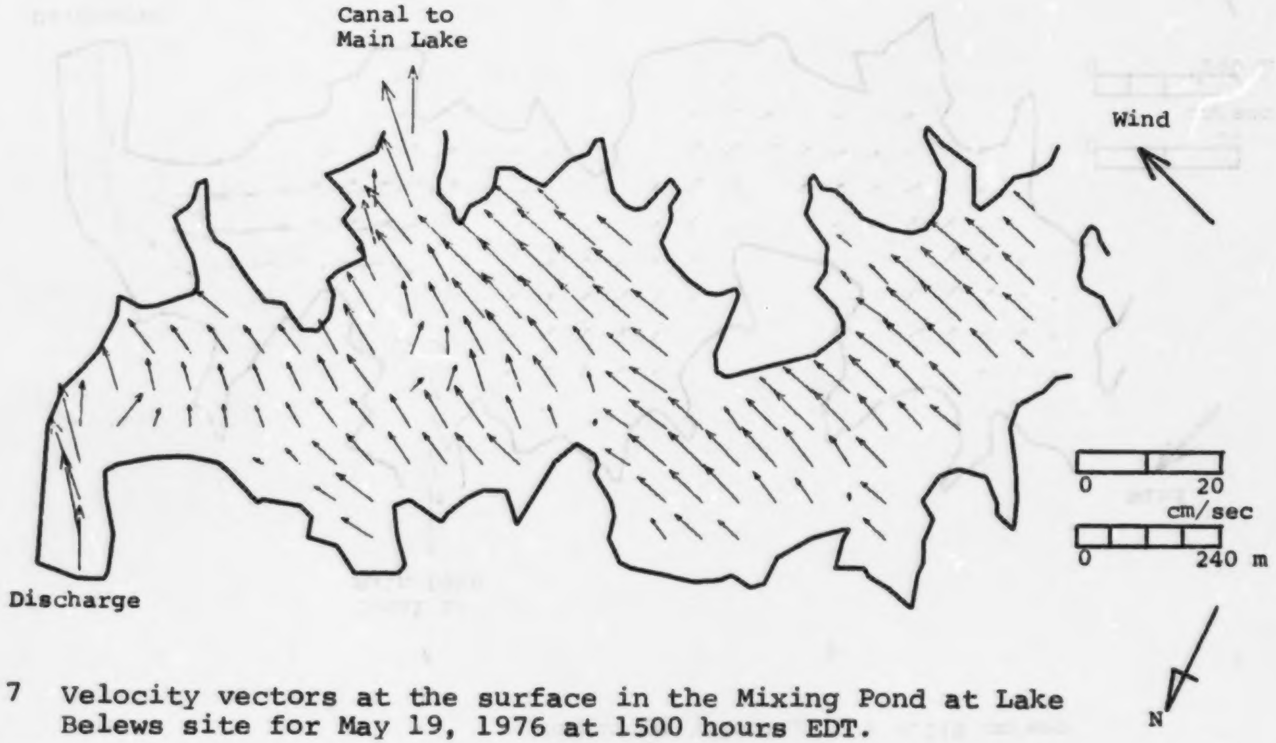

Canal to
Main Lake
Wind
0
20
cm/sec
0
240 m
Discharge
N

Fig. 7 Velocity vectors at the surface in the Mixing Pond at Lake Belews site for May 19, 1976 at 1500 hours EDT.

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

Δt : 36 sec
Time : 1500 EDT
Wind : 6.4 m/sec (14.2 mph)W
Plant Discharge : 190×10^{6} kg/hr
Horizontal Diffusivity: 15,000 cm^{2}/sec
Air Temperature : $19.1^{\circ}C$
Discharge Velocity : 9.218 cm/sec

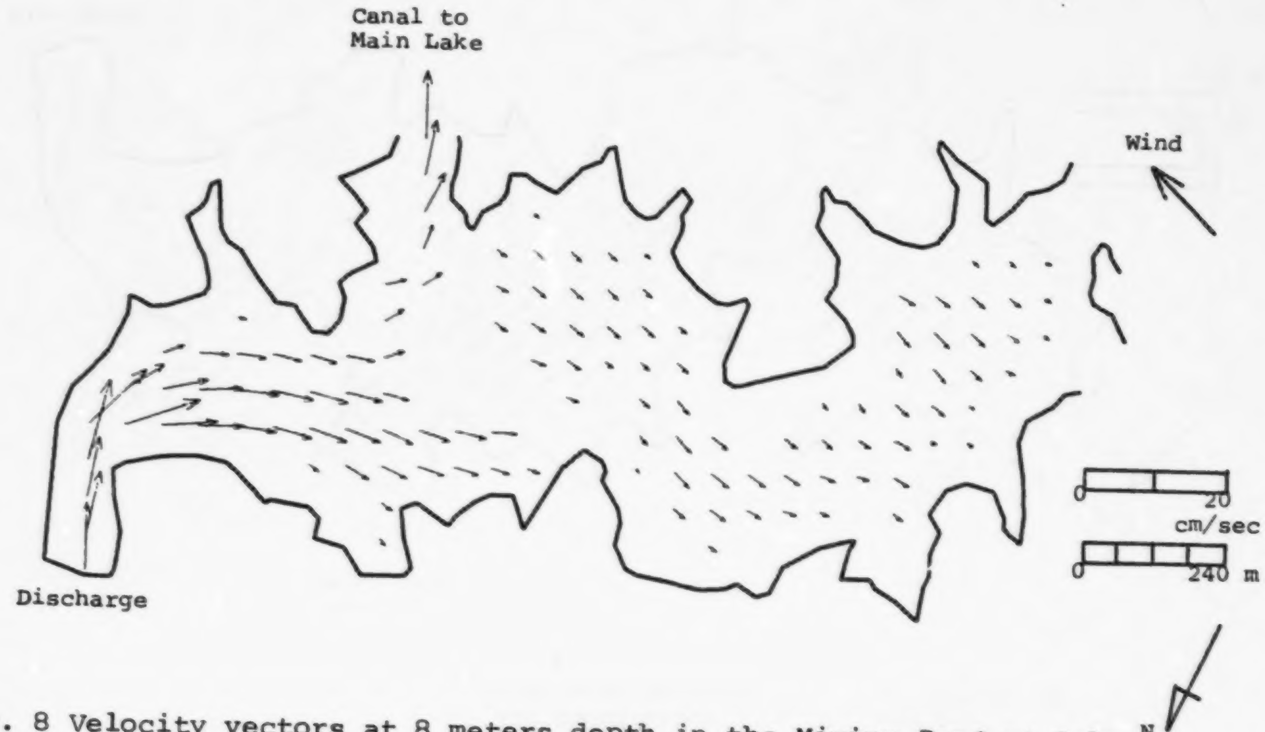

Canal to
Main Lake
Wind
Discharge
0
20
cm/sec
0
240 m
N

Fig. 8 Velocity vectors at 8 meters depth in the Mixing Pond at Lake Belews site for May 19, 1976 at 1500 hours EDT.

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

Δt :36 sec
Time :1500 EDT
Wind :6.4 m/sec (14.2 mph)W
Plant Discharge :190×10^6 kg/hr
Horizontal Diffusivity :15.000 cm^2/sec
Vertical Diffusivity :10 cm^2/sec
Air Temperature :19.1 °C
Discharge Velocity :9.218 cm/sec

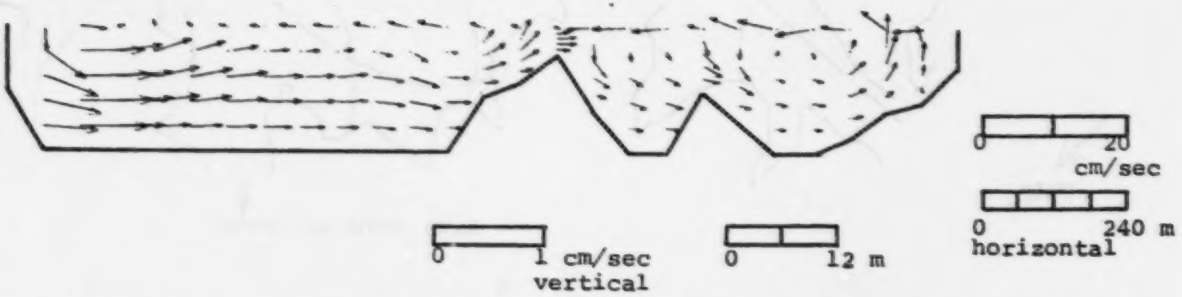


Fig. 9 Velocity distribution at vertical cross section along J=4 in Mixing Pond at Lake Belews site for May 19, 1976.

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

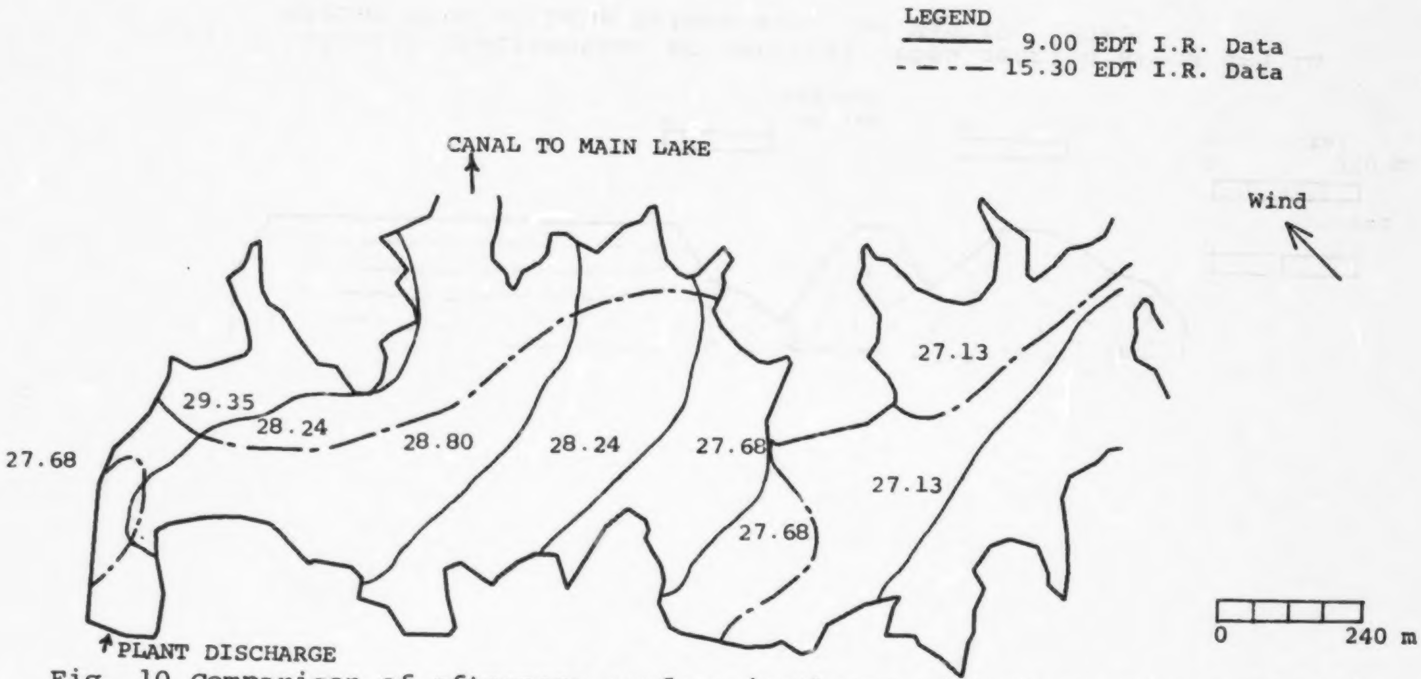

LEGEND
9.00 EDT I.R. Data
15.30 EDT I.R. Data
CANAL TO MAIN LAKE
Wind
27.68
29.35
28.24
28.80
28.24
27.68
27.13
27.13
27.68
0
240 m
PLANT DISCHARGE
N

Fig. 10 Comparison of afternoon surface isotherms with the morning surface isotherms in the Mixing Pond on May 19, 1976 at the Lake Belews site.

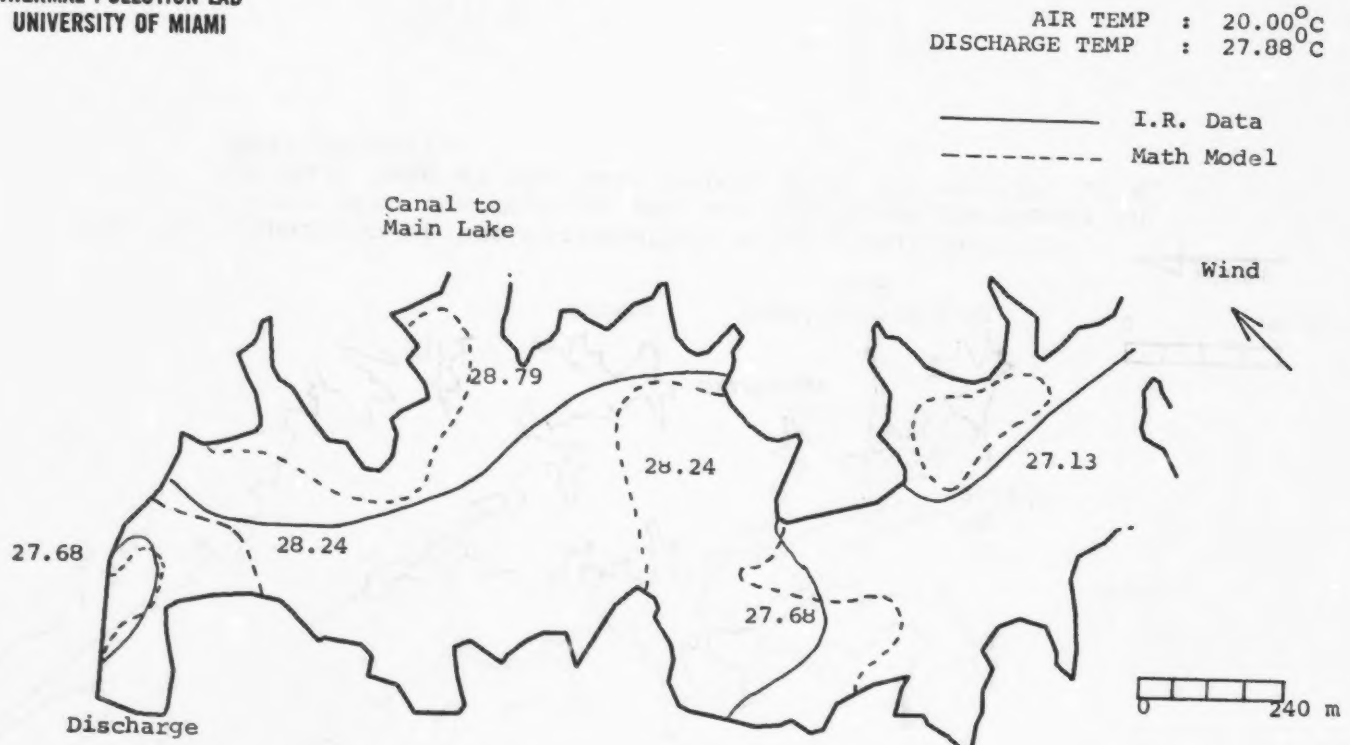

AIR TEMP : 20.00°C
DISCHARGE TEMP : 27.88°C
I.R. Data
Math Model
Canal to Main Lake
Wind
28.79
28.24
27.13
27.68
28.24
27.68
Discharge
0
240 m
N

Fig. 11 Comparison of Surface Isotherms As Obtained by Mathematical Model for Mixing Pond with Those Obtained By Infra-red Remote Sensing on May 19, 1976 At 15.30 At Lake Belews Site

THERMAL POLLUTION LAB
UNIVERSITY OF MIAMI

Δt : 36 sec
Total Time : 1500 EDT
Wind : 6.4 m/sec (14.2 mph) S.W.
Plant Discharge : 191 x 10^6 kg/hr
Horizontal Diffusivity : 1,500,000 cm^2/sec
Vertical Diffusivity : 10 cm^2/sec (constant)
Air Temperature : 19.1°C (66.4°F)
Depth : 9.14 m (30 feet) (constant)

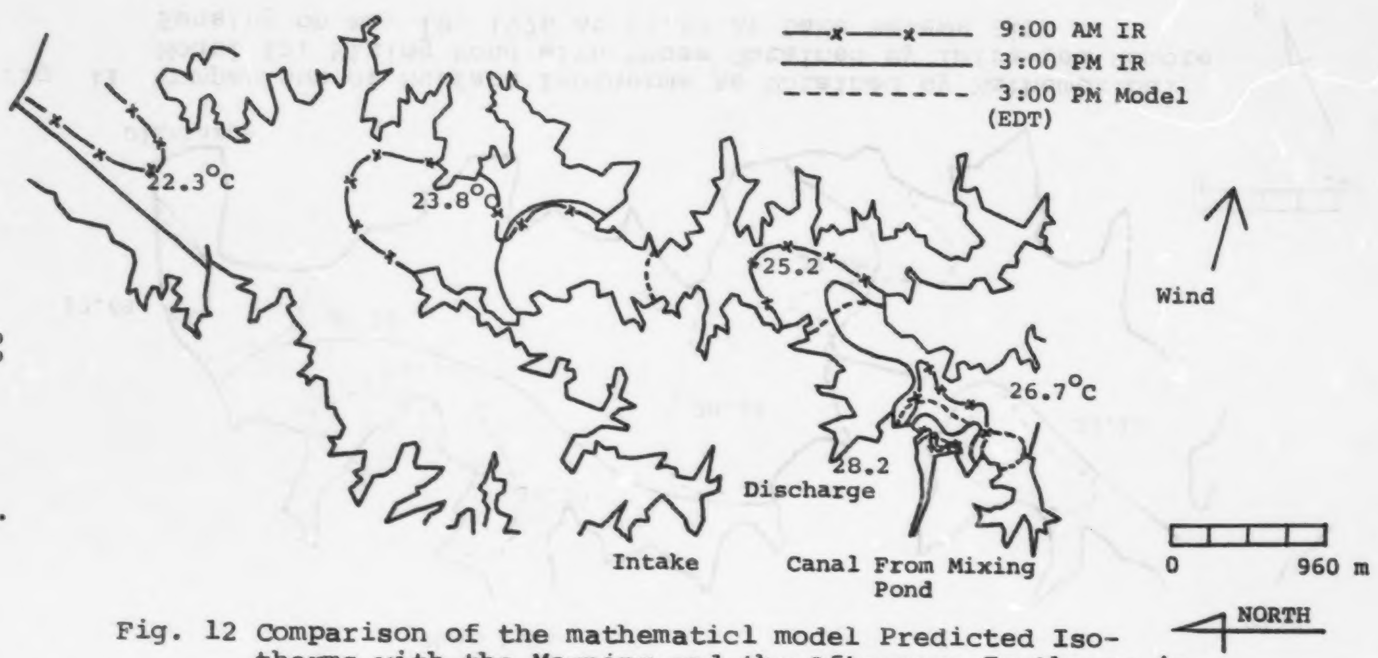

—x—x— 9:00 AM IR
——— 3:00 PM IR
- - - - 3:00 PM Model
(EDT)
22.3°C
23.8°C
25.2
26.7°C
28.2
Discharge
Intake
Canal From Mixing Pond
Wind
0
960 m
NORTH

Fig. 12 Comparison of the mathematicl model Predicted Isotherms with the Morning and the Afternoon Isotherms in the Main Lake at the Lake Belews Site for May 19, 1976. (Preliminary)

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SESSION IX-A
UTILIZATION V

10-45-13

IX-A-3

THE SHERCO GREENHOUSE: A DEMONSTRATION OF THE BENEFICIAL USE OF WASTE HEAT

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ABSTRACT

Northern States Power Company's new Sherburne County Power Plant (Sherco) is producing more than electricity. It is also demonstrating that condenser reject heat produced during the power generation process can be used to grow vegetables and flowers during the harsh Minnesota winter.

The Sherco Greenhouse project is a cooperative effort of Northern States Power Company, the University of Minnesota, and the U.S. Environmental Protection Agency. The 1/2 acre demonstration greenhouse was built in the Fall of 1975 and was first heated with condenser reject heat in September 1976. Condenser reject heat in the form of warm water is piped more than 1/2 mile from the Sherco Unit #1 cooling tower to finned tube heat exchangers used to heat the greenhouse air. This same warm water is also circulated through a grid of buried plastic pipes to heat the greenhouse soil. The warm water, cooled some 5-10°F, is then returned to the cooling tower basin.

Experience has shown that the warm water heating system is able to supply all of the greenhouse heating requirement from condenser reject heat when outside air temperatures are as low as -40°F. The corresponding greenhouse temperature of 55-60°F (which occurs only on the coldest nights) is acceptable for the production of roses, snapdragons, tree seedlings, tomatoes, and lettuce.

INTRODUCTION

Investigation of the beneficial use of waste heat* has been underway at Northern States Power Company (NSP) since 1970. Concepts proposed by Sam Beall and others at Oak Ridge National Laboratories were piloted in a 2000 ft^2 commercially operated greenhouse in Minneapolis during 1974 and 1975. Encouraging results from this pilot research effort led to an award from the U.S. Environmental Protection Agency to demonstrate the technical and economic feasibility of using power plant waste heat in a larger scale, 1/2 acre greenhouse.

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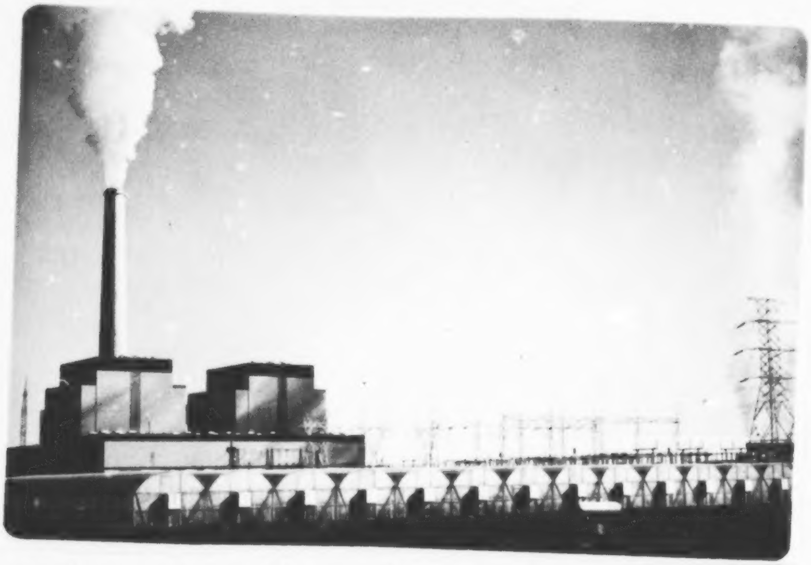
*Heat rejected from the condenser to cooling water which is generally available at 85°F in closed cycle wet cooling tower systems.

The Sherco Greenhouse, as it is now called, is a cooperative effort of NSP, the University of Minnesota, and the EPA. The greenhouse was built in the Fall of 1975 and heated during 1975-76 with simulated waste heat (because the power plant was still under construction). Since September, 1976, the Sherco Greenhouse has been using waste heat from Sherburne County Unit #1 condenser cooling water.

DESCRIPTION OF FACILITIES

Power Plant



The new Sherburne County (Sherco) Power Plant is a two unit coal-fired station with a total rated output of 1,360 MW. The plant is located about 45 miles northwest of Minneapolis, Minnesota. It features a limestone scrubber system for air pollution control and closed-cycle mechanical draft wet cooling towers for thermal pollution control. The first unit, which began operating in early 1976, has a condenser cooling water flow of 250,000 gpm and a design cooling water Δt of 29°F. The winter design minimum cooling water condenser outlet temperature is 85°F. This is the design water temperature for the warm water greenhouse heating system.

Greenhouse

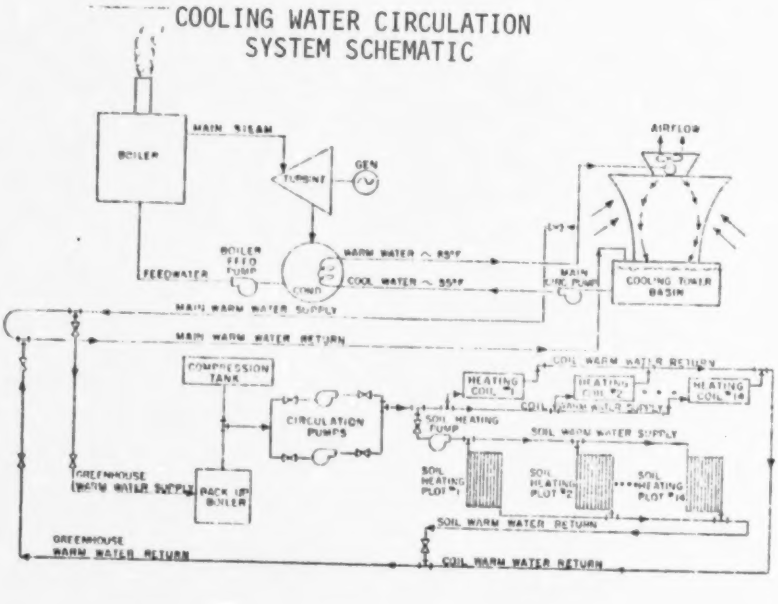
The greenhouse is a conventional gutter-connected style with a double layer polyethylene plastic roof and sidewalls. The greenhouse consists of 14 connected bays each measuring 17' X 96' for a total enclosed ground area of 22,848 square feet.

The calculated greenhouse design heat loss is 2.2 Mega Btu/hr at -30°F

The soil heating system, which is used primarily for crop root zone temperature control, consists of polyethylene plastic pipes 1" in diameter, spaced 2'-0" on center and buried about 12" below the soil surface. The 1" pipes are headered together in groups of 8 per bay and supplied with warm water on one end with return taken from the header at the opposite end 96' away. The design flow rate is about 1 gpm/pipe while the design Δt for 85°F supply water is 10°F assuming a 50°F soil surface temperature and a 60°F root zone temperature. The system is controlled by soil temperature sensing thermostats that start and stop circulating pumps.

The main water supply and greenhouse internal circulation are illustrated schematically in Figure 1. The 85°F warm water is tapped off Sherco Unit #1 at the cooling tower supply riser pipe and transmitted 3,500 feet (one way distance) to the greenhouse. The pipe conveying the warm water is 12" diameter Lo-head PVC plastic, uninsulated; and, buried to a nominal depth of 5'-0". The pipeline can deliver 1600 gpm, which is about 1100 gpm more than needed by the 1/2 acre greenhouse.

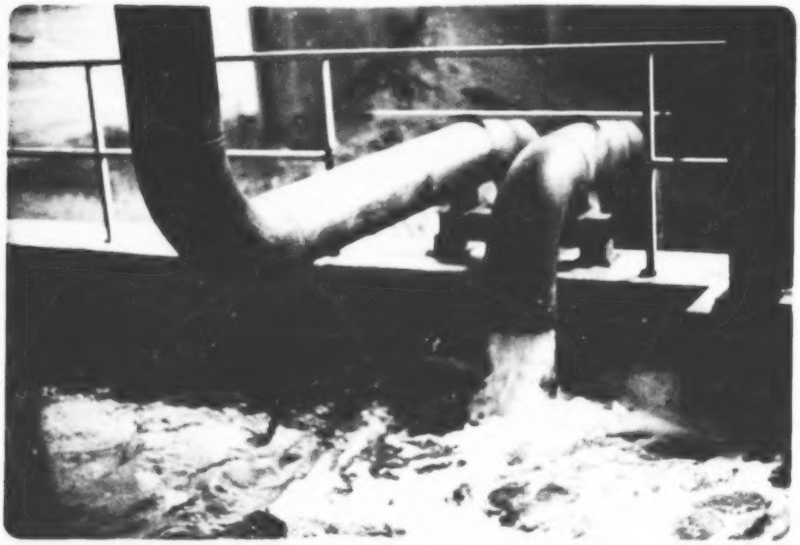
Fig. 1



COOLING WATER CIRCULATION
SYSTEM SCHEMATIC

BOILER
MAIN STEAM
TURBINE
GEN
AIRFLOW
BOILER FEED PUMP
FEEDWATER
COND
WARM WATER ~ 85°F
COOL WATER ~ 55°F
MAIN CIRC PUMP
COOLING TOWER BASIN
MAIN WARM WATER SUPPLY
MAIN WARM WATER RETURN
COMPRESSION TANK
CIRCULATION PUMPS
COIL WARM WATER RETURN
HEATING COIL #1
HEATING COIL #2
HEATING COIL #14
COIL WARM WATER SUPPLY
SOIL HEATING PUMP
SOIL WARM WATER SUPPLY
GREENHOUSE WARM WATER SUPPLY
BACK UP BOILER
SOIL HEATING PLOT #1
SOIL HEATING PLOT #2
SOIL HEATING PLOT #14
SOIL WARM WATER RETURN
GREENHOUSE WARM WATER RETURN
COIL WARM WATER RETURN

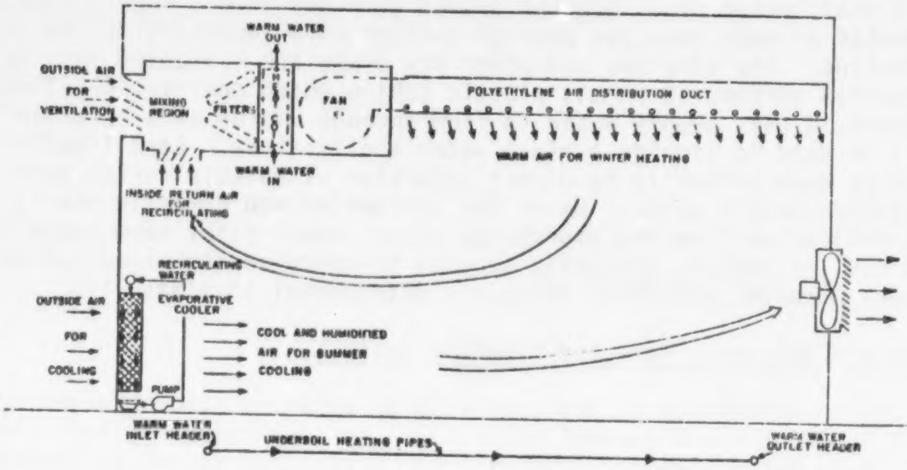
From the main supply pipeline, water is pumped through the greenhouse heat exchangers by four 5 Hp pumps each capable of about 150 gpm circulation. The pumps operate in parallel with the number of pumps operating, determined by the number of greenhouse bays calling for heat. The design water flow rate is 406 gpm for air heating and 112 gpm for soil heating or a total circulation of 518 gpm. The maximum design water Δt is about 10°F. After passing through the greenhouse heating system, the water is returned to the 12" main pipeline and transmitted back to the cooling tower basin. A larger scale application would eventually require further cooling of the water or redesign of the power plant condenser to match the smaller 10°F Δt achieved in the greenhouse application.



Cooling System

The greenhouse cooling system is shown schematically in Figure 2. A 36" high Cel Dek evaporative cooler is mounted vertically along the entire north wall of the greenhouse. Conventional water, not power plant warm water, is recirculated over the evaporative cooler at a rate of about 120 gpm. Air is drawn through the cooler by fourteen 36" diameter propeller exhaust fans located in the greenhouse south wall. The total design cooling airflow is 179,000 cfm. The cooling system is controlled by thermostats in each bay starting and stopping the exhaust fans.

Fig. 2 HEATING AND COOLING SYSTEM SCHEMATIC


WARM WATER OUT
OUTSIDE AIR FOR VENTILATION
MIXING REGION
FILTERS
FAN
POLYETHYLENE AIR DISTRIBUTION DUCT
WARM AIR FOR WINTER HEATING
WARM WATER IN
INSIDE RETURN AIR FOR RECIRCULATING
RECIRCULATING WATER
EVAPORATIVE COOLER
OUTSIDE AIR FOR COOLING
COOL AND HUMIDIFIED AIR FOR SUMMER COOLING
PUMP
WARM WATER INLET HEADER
UNDERSOIL HEATING PIPES
WARM WATER OUTLET HEADER

Control System

The overall greenhouse control system is predicated upon a philosophy of simple on-off thermostatic control. Temperature is the only automatically controlled variable. Each bay of the greenhouse has two thermostats, one for heating and one for cooling. The greenhouse is further divided into two separate control zones each consisting of 7 bays. A central control and status indicator panel facilitates selection of modes of operation, e.g., cooling vs. heating and it also allows selection of outside air or return air for heating mode operation for each zone of control. With these manual selection features it is possible to control both relative humidity and temperature and to maintain different growing environments in each half of the greenhouse. As mentioned before, heating thermostats provide pump starting signals for primary water circulation through the greenhouse heat exchangers; while soil heating thermostats provide pump starting signals to soil heating system secondary booster pumps. In addition to pump starting, the thermostats also enable fan starting in each bay and initiate opening of return or outside air dampers as the centrifugal air handler motors are starting. It is necessary to start the centrifugal air handlers with both dampers closed to prevent rapid inflation damage to the polyethylene air distribution ducts.

Irrigation and Fertilization

Irrigation of crops in the Sherco greenhouse is accomplished by two different systems. The rose irrigation utilizes a bed perimeter spray system in which small nylon spray nozzles tapped directly into a supply pipe on the perimeter of each rose bed provide uniform water applications by surface sprinkling. The tomatoes and other row crops are irrigated by a trickle irrigation system. A porous plastic tubing which operates by allowing low pressure, 4 psi, supply water to flow through micron-size pores in the tube wall, is used to provide surface water applications. Fertilization of all crops is done primarily by direct injection of soluble fertilizers into the irrigation supply water. Water for irrigation and domestic use is provided by a drilled well on the greenhouse site. Power plant warm water is not used for irrigation, primarily because it contains dissolved solids and various chemical additives which are detrimental to plant life.

Alarm and Emergency Heat and Electric Systems

The Sherco greenhouse is equipped with an advanced warning/alarm system, which monitors three parameters critical to the heating system. Greenhouse project personnel are notified of alarm conditions caused by greenhouse air temperatures below 50°F (in the event of mechanical equipment failure), by warm water supply water temperatures below 75°F (in the event of an unscheduled power plant outage) and by an electrical power interruption. Since the greenhouse electric power is not supplied by the Sherco plant, two electric boilers are used as a standby heat source in the event of a plant outage. The two 390 kilowatt electric hot water boilers were used during the 1975-76 heating season to supply warm water for heating which simulated power plant warm water design conditions. In the event of an electric power interruption, a separate emergency heating system is used. A 10 kilowatt, propane-fueled electric generator is used to provide emergency power for lighting and portable propane heater operation. Six 350,000 Btuh, propane fired forced-air heaters can be deployed in the greenhouse to provide heat until normal electric service conditions are restored.

Data System

In order to provide an adequate environmental history and to assess the technical feasibility of the use of warm water for greenhouse heating, an instrumentation scheme is used to monitor pertinent physical conditions of the Sherco greenhouse.

The scheme used for measurement of inside greenhouse temperatures consists of ten individual points in each of the 14 bays of the structure. At three random locations in each bay, three dry bulb temperatures are recorded. The three temperatures monitored at each location include one soil temperature (at random depths; 4 to 12 inches below grade), one air temperature below the plant canopy and one air temperature near or above the plant canopy level. Dew point temperature is also monitored at one of the three locations in each bay. Ambient air dry bulb and dew point temperatures are monitored at one location.

Total incident solar radiation is recorded at one location inside the greenhouse and one outside location at the greenhouse roof elevation.

The remainder of the recorded points include greenhouse warm water supply and return temperatures, soil heating supply and return water temperatures, greenhouse warm water flow rate and air and water supply and return temperatures on four of the heat exchange units.

Greenhouse warm water cumulative flow, soil heating water cumulative flow and electrical power consumption of circulating water pumps, heating fans and exhaust fans are recorded on a daily basis from manually read meters.

Dry bulb air and soil temperatures are measured with 24-gage, copper-constantan thermocouples, air dew point temperatures are measured using lithium-chloride heated electrical hygrometers and water temperatures are measured with immersion type copper-constantan thermocouples. Incident solar radiation is measured by star pyranometers and recorded as hourly integrated values.

The 227 points monitored are scanned and recorded at one-half hour intervals by a microprocessor controlled data acquisition and recording system. Data is recorded on a paper tape printer for on-site observation and also on magnetic tape for processing at a central computer location. The data thus procured is processed to indicate time-function plots of environmental and warm water conditions. This data is also used as the basis for establishing the overall energy balance of the greenhouse system.

RESULTS OF OPERATION

The winter of 1976-77 has gone on record in Minnesota as one of the coldest ever. It was the coldest October through January recorded in the last 100 years and the second coldest ever on record. Throughout this extremely cold winter season, the Sherco greenhouse received its heat almost exclusively from condenser cooling water. (Heat from Sherco Unit #1 was unavailable when the plant was forced out of service and during scheduled start ups and shut downs when the water temperature was too low to be useful).

Warm water heating system performance data are shown in Figures 3 and 4 for the coldest day of the 1976-77 heating season. The inside air temperature plotted in Figure 3 is an average of air temperatures measured at about 60" above the greenhouse floor at three locations down the 96' length of a single bay. The greenhouse inside air temperature was maintained at 58°F when the corresponding outside air temperature was -42.6°F at 8:00 a.m. on January 9, 1977. The corresponding greenhouse supply water temperature from Sherco #1 condenser was 90.9°F and the water Δt was 5.1°F.

It has been found that the warm water has been available at higher temperatures, approximately 90-100°F, during the most severely cold weather. The reasons for this are twofold. First, when it is severely cold, NSP electric system demands are high and; hence, generator output on Sherco Unit #1 is near maximum. Second, when ambient air temperatures drop to -20 or -30°F

Fig. 3

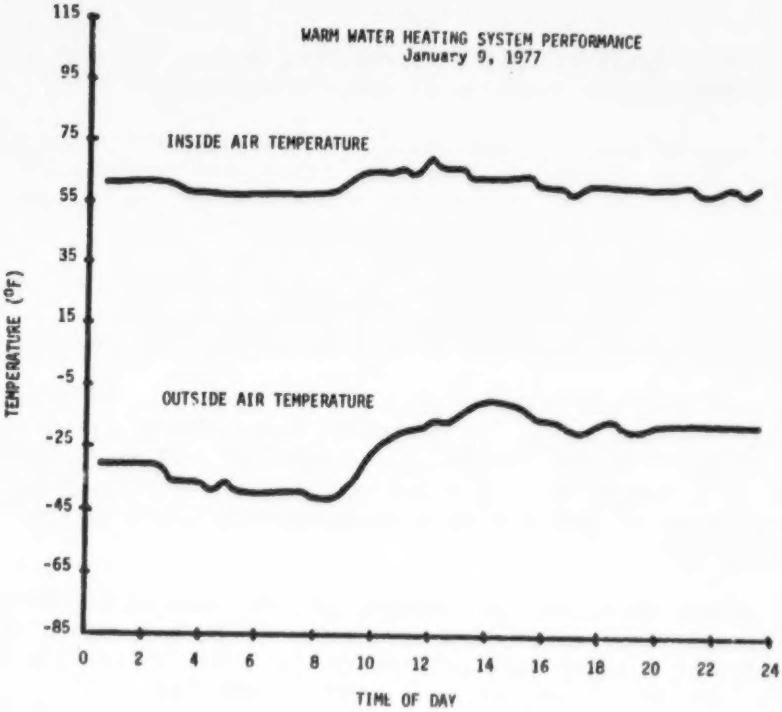
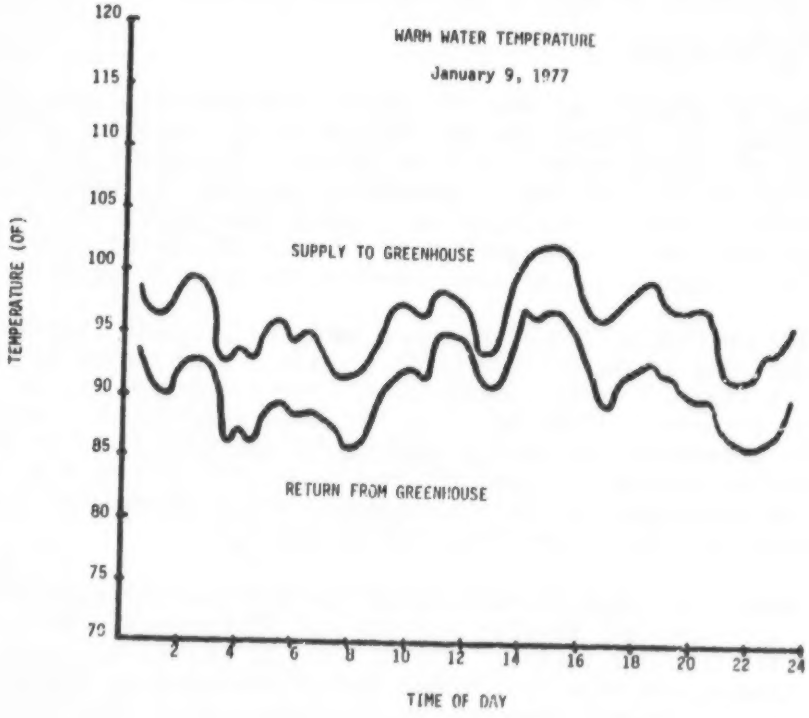

WARM WATER HEATING SYSTEM PERFORMANCE
January 9, 1977
INSIDE AIR TEMPERATURE
OUTSIDE AIR TEMPERATURE
TEMPERATURE (°F)
115
95
75
55
35
15
-5
-25
-45
-65
-85
0
2
4
6
8
10
12
14
16
18
20
22
24
TIME OF DAY

Fig. 4


WARM WATER TEMPERATURE
January 9, 1977
SUPPLY TO GREENHOUSE
RETURN FROM GREENHOUSE
TEMPERATURE (OF)
120
115
110
105
100
95
90
85
80
75
70
2
4
6
8
10
12
14
16
18
20
22
24
TIME OF DAY

plant operators increase the condenser outlet water temperature to minimize the potential for local ice formation in the cooling towers.

It has also been observed that the warm water temperature available is strongly dependent upon generator unit output. Table I summarizes typical generator unit electrical loadings and corresponding condenser outlet and greenhouse supply water temperatures. The greenhouse and ambient air temperatures are also shown to indicate the total relationship amongst the variables. However, the higher daytime temperatures in the greenhouse result more from solar heat gain than from higher warm water temperatures.

TABLE I
TEMPERATURE VARIATIONS WITH GENERATOR OUTPUT
(November 12, 1976)

TIME	GENERATOR OUTPUT (MWE)	WATER TEMPERATURES		AIR TEMPERATURES	
		COOLING WATER OUTLET (°F)	GREENHOUSE SUPPLY (°F)	GREENHOUSE (°F)	AMBIENT (°F)
0000	278	78.7	75.6	58.0	18.8
0200	282	79.3	78.7	58.9	21.1
0400	381	91.0	91.1	60.8	21.6
0600	399	93.3	95.8	61.7	20.7
0800	404	92.1	89.3	60.3	19.3
1000	411	91.8	84.0	65.1	22.1
1200	579	90.1	88.4	67.7	25.4
1400	656	92.8	89.8	67.3	26.8
1600	693	91.7	90.7	61.7	28.2
1800	690	92.1	92.0	60.8	20.2
2000	689	31.1	90.7	60.8	17.8
2200	631	91.4	89.8	60.3	16.4
2400	397	78.9	81.4	57.1	16.4

Crops

Since January, 1976 the Sherco greenhouse has been fully planted. Five of the fourteen bays are planted with several different varieties of long stem and sweetheart roses. Of the remaining nine bays, eight were used for tomatoes and one for green peppers. Following the first tomato and green pepper harvest in the Spring of 1976, the same bays were rotated with snapdragons and lettuce during the Summer and Fall of 1976. After the fall lettuce crop, tomatoes were again planted in seven bays in February, 1977. One of the remaining bays is cropped with potted geraniums and the other with containerized tree seedlings and nursery liner stock.

The objective of the cropping program has been to demonstrate that a variety of crops can be grown in a greenhouse heated with warm water. Though yields achieved may be less than those of commercial greenhouse operators, quality has been good to excellent. All floral and vegetable products grown have been marketed in the Minneapolis area. Table II summarizes the yields of the various crops as of February, 1977.

TABLE II
CROP YIELDS

Crop	Yield	Time Period	Greenhouse Area (ft^2)
Roses	125,000 stems	Feb 1976-Feb 1977	8,160
Snapdragons	15,400 stems	Aug 1976-Jan 1977	6,528
Geraniums	4,800 (4" pots)	(Planted but not yet harvested)	1,632
Coniferous Tree Seedlings	3,000 units		340
Tomatoes	25,000 lbs	Jan-July 1976	13,056
Lettuce	3,500 lbs	Aug 1976-Jan 1977	6,528
Green Peppers	1,400 units	Jan-July 1976	1,632

PROBLEM AREAS

Fouling

The most troublesome problem encountered in the entire greenhouse operation has been water side fouling of heat exchangers and associated piping. Fouling first became apparent when performance tests on individual heat exchangers showed heat transfer coefficients as low as 50% of design specified levels. Investigation of the problem is still underway, but thus far it is known that deposits of organic and silt materials build up on pipe and heat exchanger tube walls. Inspection of sections of a 6" pipeline have shown deposition thicknesses of up to 1/8". The main 12" diameter warm water supply pipeline from the cooling tower now delivers only 1000 gpm; whereas the measured flow rate was 1600 gpm upon initial start up in September, 1976. This flow loss is believed to be the result of deposits on the pipe wall.

So far, both chlorination and acid cleaning of the heat exchangers have been effective in improving heat transfer coefficients. Typically heat exchanger performance improves to 80-90% of design immediately after a chemical cleaning cycle, but the performance again degrades to the 50-60% level in a matter of a few days.

Plans are underway to attempt to clean the deposits from the 7000 feet of 12" pipeline. If successful, a program of periodic chemical cleaning will be initiated to limit the despositions within tolerable flow performance limits. It is believed that if the deposition problem in the pipeline is controlled, that the heat exchanger fouling problem will also be mitigated.

Plume Shading

It has been observed that, during periods of ambient conditions not conducive to vapor dissipation, cooling tower vapor plumes can present a shading effect which may alter greenhouse crop production. Although full documentation is not available at the present time, it is felt that the particular location of the Sherco greenhouse with respect to the cooling towers does not pose any serious lighting problems. For future developments a computer simulation relating local ambient conditions to cooling tower plume shading is being proposed. This, together with information on greenhouse proximity requirements as it relates to warm water delivery costs, generating plant layout and local geographic conditions, will form the basis for choosing optimum warm water greenhouse sites.

ECONOMICS

The economic feasibility of using warm water for greenhouse heating is dependent upon the price differential between warm water and other alternative fuels such as oil, electricity, or natural gas. It is the annual operating energy cost differential which must justify the greenhouse owner-operator's additional investment in larger heat exchangers required to utilize waste heat.

In the case of the Sherco greenhouse, the cost to deliver warm water 3,500 feet to the greenhouse and return it the same distance to the cooling tower is about $1.35/Mega Btu. This figure is calculated on the basis of an actual installed pipeline cost of $84,000, a pipeline flow rate of 1500 gpm, 10 Hp per acre pipeline pumping power, and 7400 Mega Btu/acre-yr greenhouse heat requirement.

Alternative fuel costs as of February, 1977 for residential size customers in Minneapolis were as follows:

Electricity	1.9¢/kwh	$5.57/Mega Btu
Gas	19.8¢/therm	1.98 " "
Oil	44.9¢/gallon	3.21 " "

Oil and natural gas costs shown in dollars per Mega Btu should really be adjusted by the energy conversion efficiency of the heating system used to arrive at a comparable cost in dollars per Mega Btu of useful heat in the greenhouse. However, since greenhouse operators generally pay less than residential rates for energy, no adjustment for heating system efficiency will be made.

Comparing the fuel cost of oil to warm water, then, there is a cost differential of $1.86/Mega Btu favoring warm water. Or on an annual basis a savings of $13,764 per acre could be realized by the warm water user. It should be noted that this savings is in real current dollars based on real current fuel costs.

Of course there are also greater incremental operating costs associated with using warm water. Specifically, it is estimated that incremental electric power usage would be about 175,000 kwh/acre-yr; which, at present NSP electric rates, amounts to an additional electric operating cost of $3,500/acre-yr. (The actual total electric power consumption for circulating water pumps and heat exchanger fans in the Sherco greenhouse was 73,786 kwh for the period October 1, 1976 to March 1, 1977). So, the final net annual savings that a greenhouse owner-operator would realize is $10,264/yr. And, depending upon the owner-operator's financial structure, an additional investment in heat exchanger equipment of about $90,000 per acre might be justifiable. (The actual delivered heating system equipment cost for the Sherco greenhouse was $47,912).

CONCLUSION

It is believed that the Sherco greenhouse has met the stated project objective to demonstrate technical and economic feasibility of utilizing power plant waste heat for greenhouse heating. Fortifying this conclusion are numerous inquiries and some serious discussions with potential warm water users. NSP plans to commercialize the use of warm water for greenhouse heating within the next 1-2 years at the Sherburne County Plant site. Initially warm water will be provided from Units 1 and 2 to an area suitable for about 14 acres of greenhouses. Beyond this development, consideration will be given to providing service to a larger land area capable of accommodating 100 or more acres of greenhouses.

DECENTRALIZED ENERGY CONVERSION FOR WASTE HEAT UTILIZATION

J. R. Schasfgen
U. S. Department of Commerce
National Bureau of Standards
Washington, D. C

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IX-A-19

WASTE HEAT EMPLOYMENT FOR ACCELERATED REARING OF COHO SALMON

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Seattle, Washington U.S.A.

ABSTRACT

Studies conducted at the College of Fisheries, University of Washington on the use of waste heat to accelerate growth of coho salmon (Oncorhynchus kisutch) have shown that a year reduction in freshwater rearing can be induced, without altering the marine residence period of this species. The result of this strategy has been to reduce coho generation time from three to two years, with substantial savings in hatchery production costs and increased biomass return. Application of this concept is considered in utilization of industrial waste heat.

INTRODUCTION

Pacific salmon are one of the great fishery resources of the United States and Canada. In the past, annual landings have reached as high as 650 million pounds, which attests to the fact that the production capacity of this resource was very large. Even in those years of high production, however, the limiting factors that prevented even larger returns were related to restricted stream capacities for the spawning adults and for the rearing progeny.

With the magnitude of the sport and commercial salmon fisheries and further restraints being placed on natural populations through the loss and degradation of freshwater habitats, natural production of salmon is no longer sufficient to sustain the fishery. To overcome the problem of declining salmon resources, fisheries management agencies have put considerable effort in hatchery development, with a total of 82 hatcheries operating in the United States, mainly in California, Oregon and Washington, by 1974 (National Task Force Report 1976). Artificial propagation of salmon through hatchery production already is responsible for a substantial share of the fishery. In the great Columbia River Basin, for instance, hatchery releases amount to 170 million fish annually, (Ortmann et al 1976) which in turn account for 50% of the harvested salmon and steelhead (C.B.S.S.A., 1976) in that system. In Washington State, more than 50 percent of the harvested coho and chinook salmon are of hatchery origin, and in some locations such as southern Puget Sound, hatchery contribution approaches 70 percent. At the present time, large enhancement programs have been planned by state and federal agencies in Alaska, British Columbia and Washington which will increase artificial production of salmon by as much as 300 percent on the eastern Pacific Coast over the next decade. Much of the proposed production will come from coho salmon propagation, and the use of waste heat could be employed to help reach this production goal by improving the culture environment of this species.

BACKGROUND

Coho salmon (Oncorhynchus kisutch) occur in innumerable streams on the north American coast from Monterey Bay, California, north to Point Hope, Alaska (McPhail and Lindsey 1970), with the center of abundance in Puget Sound in the State of Washington.

The adult coho leave the sea in the fall and ascend the rivers and streams to spawn. Most of the spawning takes place in November. Incubation of the eggs takes 3 to 6 months, depending upon the temperature of the water. The young fish emerge from the gravel in the spring and spend their first year feeding in the small streams, migrating to sea in the second year, about 18 months from the time the eggs were deposited. In the sea, growth is rapid and a few male fish (jacks) return to spawn at 2 years of age, but most return as adults at 3 years of age. In the more northern part of the range, coho may spend 30 months in freshwater growing to the smolt stage and return to the spawning streams at 3 to 5 years of age.

Coho salmon produce a large number of eggs (3,500±). The overall natural mortality in fresh and salt water, however, is great. Shapovalov and Taft (1954) were able to calculate overall survival at Waddell Creek, California, on six brood years and found that survival varied from 0.02 to 0.30 percent, with a mean of 0.13 percent, or about two spawning pairs for each pair of parent fish, with the greatest mortality having occurred during incubation and stream residence.

Hatchery propagation in contrast can be very good. Mortalities during incubation and rearing in fresh water may be as low as 10 or 15 percent up to the time of smolt release. Although subsequent marine mortalities may exceed the percentage lost among natural populations under marine conditions, over the last 15 years improved hatchery technology has greatly increased survivability of cultured fish once in the marine environment. Studies by the Washington State Department of Fisheries have shown that the best coho survival was obtained when hatchery fish were reared twelve months after incubation and released close to the natural migratory timing (Salo and Bayliff 1958). Following this rearing strategy, evaluation of the coho program in the state at 13 hatcheries in 1964 showed that total survival (catch plus escapement) averaged 7.28 percent (ranging from 11.07% to 1.68% between areas) with mean return to the hatchery amounting to 1.46 percent (range 4.52% to 1.46%). Evaluations have demonstrated also that increased size of hatchery smolts during the normal period of migration has a substantial benefit to subsequent survival in the marine environment (Senn et al 1977, Feldmann 1974).

Research programs at the College of Fisheries, University of Washington, have included considerable emphasis on the culture of salmon, and methods that can be employed to improve the quality of hatchery releases. Hatchery routine with coho salmon followed the general procedure used by state hatcheries, with 18 months of freshwater incubation and rearing, resulting in the return of predominantly 3-year-old adults. In 1967, however, experiments were initiated at the College to produce coho smolts in 6 or 7 months by the use of warmed water to accelerate growth rate, with the adults returning at two years of age instead of three.

UTILIZATION OF WASTE HEAT FOR INCUBATION AND REARING

Water supplying the College experimental hatchery is pumped from the ship canal connecting Lake Washington and Lake Union. Temperature varies with the seasons, from a low of 4.5±°C in the winter to a high of 24±°C in the summer. Incubation can take place in recycled water or in a single pass system warmed in a heat exchanger used to convert waste steam from the University power plant. Heath trays are used for incubation of eggs and alevins up to the time of initial feeding. A limited supply of heated water is available for use in the troughs and ponds, until the lake warms sufficiently for use without heating.

Spawning of coho takes place during November and December, so incubation occurs in the winter months when temperatures are coldest. Since temperature determines the rate of development during incubation and the subsequent growth rate, cold winter temperatures experienced at the experimental hatchery would require alevins incubating at a mean of 4.5°C, 134 days to reach yolk absorption and thus eggs spawned by the 1st of November would not produce feeding fry until the 14th of March. Colder incubation temperatures characteristic of many salmon hatcheries would delay initial feeding even longer. However, accelerated incubation with warmed water reduces incubation time significantly. At a mean temperature of 10.5°C, 92 days are required to reach yolk absorption, with feeding beginning by the end of January. Acceleration amounts to approximately six weeks earlier feeding of fry and a weight advantage by March 14th of three times that experienced by unaccelerated fry.

Temperatures in excess of 11°C cause increased incubation problems and mortalities. However, once rearing is underway temperatures can be increased up to 13°C without difficulty, which provides an 8 to 10°C increase over normal stream temperatures during that time of year. This degree of acceleration in both incubation and rearing allows coho to smolt by the end of May of the same year at 30 fish to the pound, or approximately 15 gms each. Under standard hatchery conditions, coho fingerlings would weigh only 2 to 2.5 gms at that time and require an additional year before smolting is induced (Figure 1).

In a series of experiments conducted at the College hatchery, coho eggs, alevins and fry were subjected to the accelerated incubation and rearing schedule beginning with the 1967 brood year and subsequently on most successive years to the present. Table 1 summarizes the number, size, date of release and return success for each brood year studied from which return data is complete. Dates of release varied a few days from year to year, and availability of warm water for 1969 and 1970 brood years was limited, because of campus construction interference, which reduced the rate of growth prior to release resulting in lower returns. From the release of 240,070 accelerated coho smolts, however, a total of 5,961 fish returned to the pond, where they were identified and assigned to the proper brood year, weighed, measured, and eventually spawned. Of the 5,961 fish that returned, only 28, or 0.47%, were precocious 1-year-old males, usually called jacks. The 2-year-old adults numbered 5,833 fish, or 97.9% of the total returns, while the 100 fish identified from marks as 3-year-old fish -- the normal age for returning coho -- made up only 1.68% of the total return.

The outstanding result from this series of experiments is the predominant return of 2-year-old adults. Accelerated incubation and rearing allowed the release of smolts a year prior to normal migratory timing without any change in the marine residence period. Generation time of the accelerated hatchery population is thus reduced from three to two years.

Size of 2-year-old adults has been similar to 3-year-old adults returning to other hatcheries in Washington, depending on their feeding distribution during marine residence. Coho residing in Puget Sound have been reported smaller (< 56 cm) than coho feeding in the ocean (> 56 cm) up to the approach of maturation (Allen 1956). Based on tagging studies, the accelerated 2-year-old coho also show distributions both in Puget Sound and in the ocean, and upon return to the College hatchery most range in size between 40 cm and 73 cm in length (1 to 11 lbs.).

Success in survival among the 2-year-old adults is shown by the average of 2.43 percent returning to the College hatchery from a total release of 240,070 smolts, and compares quite favorably with the 1.46 percent escapement of 3-year-old coho returning to the State hatcheries reported by Senn (1970).

The results of these studies show that the utilization of waste heat for reducing the hatchery rearing period of coho salmon provides several advantages. Acceleration of incubation and rearing reduces generation time without any marked influence on marine residence or growth. Less food is required and labor can be reduced in cost per unit of production. Facilities for incubation and rearing can be made available for the culture of other fish species, or if summer temperatures and water availability become critical, operations during summer months can be avoided.

APPLICATION

The utilization of waste heat from nuclear power plants to accelerate the rearing of coho salmon and steelhead trout has been proposed by Puget Sound Power and Light Company, et al. in the construction of Skagit Nuclear Power Project Units 1 and 2 (NRC, 1975). Each unit employing a boiling-water reactor will generate about 1200 MW_e and will dissipate heat by an off-stream hyperbolic-type natural-draft cooling tower. No fish mitigation is involved, but the power company plans to construct an on-site fish hatchery which will utilize waste heat from this nuclear project to warm incubation and rearing water in their fish hatchery as a part of their fisheries development program on the Skagit River.

At present the details of the proposed fish facilities have not been designed, but the consultants from the College of Fisheries, University of Washington, have developed some conceptual designs for review and evaluation by the power company and state fishery agencies. The biological advantage of using waste heat to accelerate growth of anadromous salmonids, particularly in aquatic systems such as the Skagit River, which is regularly too cold for desired development and growth during late fall and winter months, is not just a concept but it is a demonstrated reality which needs to be pursued more vigorously by fishery agencies. This does not mean an indiscriminate application of waste heat from all thermal power plants, but a careful, well-planned application of waste heat to elicit desired biological responses, such as accelerated growth of young coho salmon, young chinook salmon or young steelhead trout.

SUMMARY

1. A program designed to accelerate the growth of coho salmon during the freshwater incubation and rearing phase was carried out with six brood years.

2. A total of 240,070 coho smolts were reared in warmed water and released to migrate to sea after 6 months instead of the usual 18 months in natural waters or in the State hatcheries.

3. After a feeding period in the sea, 5,833 2-year-old adult fish returned, or 2.43% of the smolts released.

4. Among the returned fish, 28, or 0.43%, were 1-year-old precocious males; 4,833, or 97.9%, were 2 years old; and only 100 fish, or 1.68%, were 3 years old -- the age of the normal stream or hatchery reared fish.

5. The use of waste heat from industry can be used to advantage to accelerate the growth of coho salmon, reduce production costs, and make a major contribution to salmon production.

ACKNOWLEDGMENTS

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TABLE 1. Summary of releases of accelerated coho and returns of marked adults to the University of Washington pond.

Brood year	Date of release	Avg wt at release (g)	No. fish released	Date of return	No. 2-year adults returning	2-year percent return	No. 3-year adults returning	3-year percent return
1967	5/29/68	15.8	17,473	1969	219	1.25	11	.06
1969	5/25-27/70	6.06	37,342	1971	145	0.39	66	.18
1970	5/28/71	9.21	63,882	1972	1,075	1.68	21	.03
1971	5/27/72	12.11	35,100	1973	850	2.42	2	.005
1972	5/26-27/73	15.69	57,133	1974	1,851	3.24	0	.00
1973	6/4/74	15.16	29,140	1975	1,693	5.80	0	.00
		14.86	240,070		5,833	2.43	100	.05

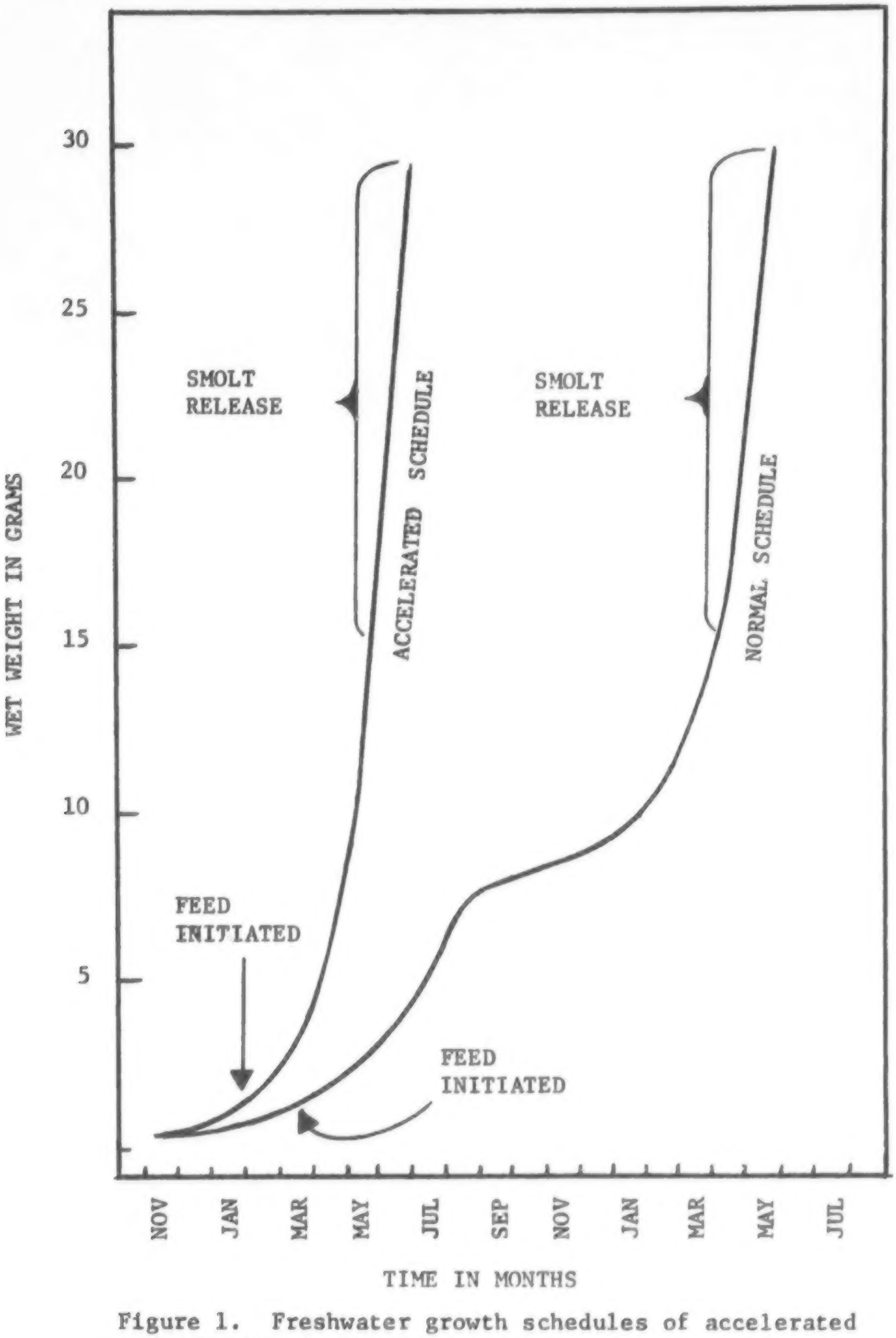

Figure 1. Freshwater growth schedules of accelerated and normally incubated and reared coho salmon up to release as smolts.

11-45-9

IX-A-29

WASTE HEAT UTILIZATION FROM A UTILITY STANDPOINT: THE PROBLEM OF IMPLEMENTATION.

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ABSTRACT

Waste heat utilization is often mentioned synonymously with power plant construction and operation. While the concept is laudable, implementation is fraught with difficulty from various quarters including legal constraints, utility operating requirements, biological considerations and economic feasibility.

LILCO is one of the few utilities which presently has actual experience in waste heat utilization. Not resting at this point, LILCO has been examining the possibility of sponsoring additional research leading to waste heat utilization at future nuclear stations. Unfortunately the Company has found that, in the intervening 7 years since it first became involved in the field, the difficulty of implementing the concept of waste heat utilization seems to have increased.

This paper examines several of the factors which must be faced by a venture contemplating beneficial uses of waste heat and offers recommendations on what proposals to utilities should address to improve their chances of success.

INTRODUCTION

The concept of waste heat utilization has been receiving a great deal of notoriety in recent years principally due to concerns for energy and the environment. As more attention is directed to the discharge of thermal effluents from electric generating stations, the value of utilizing at least a portion of rejected waste heat is becoming more evident both from an environmental and a public relations standpoint. In addition, at least on a theoretical basis, certain economic benefits can accrue to users of free waste heat that would otherwise have to be purchased.

On the negative side of the picture the development of waste heat utilization facilities is at best a difficult task due to many complicating factors. These factors are principally associated with legal constraints, utility operating requirements, biological considerations and economic feasibility.

The viability of a waste heat utilization proposal is established only after it has been shown to address and satisfy the demands of each of these. While we feel that the concept of waste heat utilization has considerable merit, under such a tough test the consideration of a specific application almost always gives rise to some serious doubts.

The Long Island Lighting Company's primary experience with waste heat utilization has been through its association with Long Island Oyster Farms, Inc. This aquaculture facility utilizes the heated discharge from LILCO's Northport Power Station to commercially spawn and raise oysters. On the basis of this experience, as well as other considerations, we believe that aquaculture represents the most practical waste heat utilization concept for utilities. Therefore, although this paper addresses waste heat utilization in general, its major emphasis is in the area of aquaculture.

LONG ISLAND LIGHTING COMPANY AND WASTE HEAT UTILIZATION

As indicated above, LILCO regards aquaculture as the waste heat utilization concept most adaptable to utility operations. Our primary basis for this opinion is the good experience we have had since 1970 with the commercially successful Long Island Oyster Farms operations at the Northport Power Station on Long Island Sound. With this influencing our judgment we have continued to welcome new proposals for additional uses of the heated effluent from our power stations. Unfortunately, however, all the proposals put forth to date have either proved to be impractical or have not been followed up by the originator.

In 1971, a private corporation expressed a desire to operate a commercial fish farm at one of our fossil plants. The operations needed 20,000 gpm of fresh water which would be pumped from wells at 52°F and heated to 78°F. Waste heat from the once-through cooling system could not be used to attain this temperature during most of the year and the cost of taking heat from the closed cooling water heat exchangers was prohibitive. The project was abandoned.

In 1974, a research institution displayed an interest in constructing an aquaculture/agriculture research facility at a nuclear facility under construction. The concept proposed would utilize the thermal effluent to heat a greenhouse. The institute proceeded with a conceptual design of the facility but never submitted a formal proposal to LILCO.

In 1975, the same research institution again expressed a desire to use the nuclear site as an experimental research facility to study the effects of power plant discharges on the biotic environment and to examine the use of heated effluents in mariculture. After review of a preliminary proposal it was determined that the use of the nuclear site was not feasible due to security and safety restrictions. A fossil site was suggested as an alternate but no further action has been taken by the institute.

In 1976, brainstorming sessions were held with representatives of several federal and state agencies concerning long-range planning for waste heat utilization from a proposed large nuclear station. Many ideas were discussed but most were rejected after examining their practicality. To date nothing has evolved from the discussions begun at these meetings.

In 1977 LILCO was approached by a private interest on the possibility of extracting heat from the steam cycle of an operating power station to heat a greenhouse for growing tomatoes. Providing this heat would have been an impossibility without noticeably affecting power plant efficiency. Faced with the prospect of access to heated discharge water only 20°F above ambient, this private interest decided to investigate the economics of supplemental heating to meet his temperature requirements in the winter. This investigation is now in progress.

What has become very apparent to those of us in the utility industry with an interest in waste heat utilization is that there seems to be an almost universal misconception regarding the ease with which waste heat may be utilized. This was in part cause for the downfall of some of the proposals discussed above.

The misconception starts with the vast majority of people believing that power plants discharge "boiling water". This, of course, is not the case since most plants release water at about 20°F over the inlet temperature. Further, they feel the plant is being terribly wasteful and inefficient while, in truth, plant design to provide electricity as the prime product has been optimized to the extent that further encroachment upon the steam cycle would only hurt efficiency. They also feel it would be easy to convert the plant from once-through or cooling towers to some sort of utilization plan. In reality, it is probably impossible to back-fit an operating station in this manner because of the tremendous capital costs involved and the questionable reliability of such a system.

On the other hand, it is true that the potential for waste heat utilization is greatly enhanced if a power plant is designed from scratch with this use in mind. In such a case, it may be possible to coordinate the power plant's cooling system with a potential nearby user e.g. a sewage treatment plant. Unfortunately, this level of coordination is virtually impossible due to the vagaries of the power plant licensing process. In the real world, when dealing with multi-billion dollar installations, it is not prudent to inexorably tie two facilities to each other when the abandonment of either would seriously affect the success of the other.

It is LILCO's view that the field of waste heat utilization would benefit a great deal if originators of different concepts exhibited more detailed attention in their proposals to the factors affecting utility decisions. A proposal, first of all, should demonstrate an understanding and knowledge of the legal constraints which are involved. Secondly, it should demonstrate that the proposed project is compatible with utility operating requirements. In the case of aquaculture projects, a proposal should clearly show that biological considerations have been adequately taken into account and that enough information exists to enable one to proceed. Finally it should address in a detailed fashion the economic feasibility of the venture.

The remainder of this paper discusses LILCO's understanding of these different factors and the information we look for when evaluating waste heat utilization proposals. The material is in no way all inclusive but does touch on most areas of concern.

Legal Constraints

The legalities of waste heat utilization span a virtually unlimited number of governmental agencies and their regulations. Most will agree, however, that the Federal Water Pollution Control Act Amendments of 1972 (the Water Act) has perhaps the greatest impact on waste heat utilization facilities.

Regulations established under the Water Act essentially prohibit the discharge of heated water. Although exemption provisions are contained in Section 316 of the Act, the burden of proof required (that aquatic biota will not be adversely impacted by either intake or discharge of water) and the prevailing attitudes of the enforcing agencies make obtaining an exemption difficult and time consuming. If a utility cannot obtain a permit to operate with once-through cooling, it must incorporate offstream cooling which almost invariably involves cooling towers. A waste heat utilization facility could, of course, also be adapted to function with offstream cooling but this would represent an additional expense. As such the concept has not been met with enthusiasm by utilities, and to our knowledge, no one has pursued this course as of yet.

Another way in which the Water Act impacts waste heat utilization is through Section 318 of the law. Under that section, proposed regulations would permit the EPA Regional Administrator to allow the discharge of pollutants to exceed effluent limitations within a designated project area if such pollutants are used in an approved aquaculture facility. However, the discharge would not be allowed to give rise to the addition of pollutants above accepted limits in navigable waters outside the project area. The regulations apply only to sites on navigable waters and only to aquaculture projects intended to produce a commercial crop with a harvest greater than would normally occur in the area.

There are two discouraging aspects of these regulations for aquaculture projects. First, since no benefit is realized by a utility in the relaxation of ultimate effluent limitations, one possible pursuasive advantage of such a project is eliminated. Second, a requirement essentially dictating that a facility must demonstrate commercial feasibility could be somewhat inhibiting. At present, we are aware of only four commercial aquaculture companies operating at power plants in the U.S. and their economic success is still being judged.

A further potential deterrent to utility involvement in aquaculture projects is the possible negative posture of a state public utility commission towards such a venture. The attitude in this regard is that electric utilities are in the power business and not the aquaculture business. Under such a commission stance, a utility might have some difficulty in "donating" land, material or even waste heat to an independent aquaculture company. In fact any association the utility might have with the project would have its problems. Under such conditions a commercial aquaculture venture might well be an impossibility.

Another federal law which represents a particular obstacle to aquaculture, but only at nuclear power plants, is the Delaney Amendment to the Food and Drug Act. (Title 21 of the U.S. Code.) Part 343 of this Amendment states that a food is adulterated if it has been intentionally subjected to radiation. Part 348, the "Delaney Clause," states that "no additive shall be deemed to be safe if it is found to induce cancer when ingested by man or animal". Unless this Amendment is modified, development of a commercial aquaculture facility at a nuclear plant in the United States would be difficult, even though a harvested crop would be well within safe radiological limits.

In addition to the "Delaney Clause", certain safety and security problems associated with nuclear plants provide additional difficulties for commercial or research waste heat facilities. In light of the recent announcement by the NRC of severely upgraded security precautions at nuclear plants, the operation of waste heat utilization facilities at a nuclear site would be indeed encumbered.

Operational Requirements

In addition to the complex legal situation discussed above, there are many operational problems and hurdles which must be considered when evaluating the potential of a waste heat utilization facility. The following list addresses some of those considerations. Although most of the points enumerated are specific to aquaculture facilities, several pertain to waste heat utilization concepts in general.

1. The power plant's prime concern is the production of power, not the utilization of waste heat. Thus, if plant operational difficulties arise, the utility's priority is to maintain a constant source of electricity and the methods used may conflict with waste heat utilization needs.

2. The amount of heated water from a power station may not be constant. As a result, in waste heat utilization projects requiring constant amounts of heated water, provisions must be made for supplemental supplies should power plant shutdowns occur. Location of an aquaculture facility must probably be limited to a multi-unit power station where there is less of a chance for all units to fail together.

3. During the summer months, the supply of heat from the power plant may be too great or not needed at all. Provisions must be made to divert heated water during those months. A waste heat utilization scheme which could make use of significant amounts of heat during this period of the year would be extremely attractive to utilities, since it is at this time in many regions that thermal discharges may have their most significant impacts.

4. Wherever possible, piping and plumbing connections to the heated water discharge should be included in the initial design of a power station to avoid costly backfitting at a later date.

5. If a facility utilizes cooling water directly from a power plant without the benefit of intermediary heat exchangers, the water quality and chemistry of the heated effluent may be of considerable concern. This is especially so for aquaculture facilities where continual monitoring is required to insure proper quality of the incoming water and to divert any undesirable effluent, such as water which has been chlorinated for the control of biofouling. During times of chlorination, alternate means of obtaining heated effluent must be provided. The pickup of minute quantities of metals from condenser tubes is another critical water quality concern. Certain metals have been shown to interfere with the successful reproduction or fertilization of sensitive organisms.

6. Rearing of low density species, such as lobsters, prawns, or agricultural crops requires a great deal of space. The acquisition of a suitable amount of land on or near a congested power plant site could present difficulties.

7. As alluded to previously, regulations concerning effluent limitations for aquaculture discharges are now under consideration by the EPA. Although the status of these are unknown at this time, it is possible that, since the majority of wastes from fish or crustacean culture are high in BOD, the discharge from an aquaculture facility may require treatment. If the facility operated on a direct-contact basis with the tremendous volumes of water discharged by a power plant, such treatment could be prohibitive.

Biological Considerations

Biological factors are an important concern in the consideration of aquaculture projects. The following biological information is necessary to evaluate the commercial feasibility of an aquaculture concept at an electric generating station.

1. In order to effectively culture a species, complete knowledge of its life-history and reproduction requirements is necessary.

2. Optimum temperature for growth of a species must be determined. This varies with the amount of food supplied as well as the age of the organism and its stage of growth.

3. The temperature required for maximum growth is often different than the temperature required for maximum food conversion. Optimization of yield versus minimization of food costs will be an important economic consideration.

4. Knowledge of the upper and lower lethal temperatures of the organism is necessary to prevent exposure to excessive effluent temperatures. The lethal temperature must also be determined for each life stage of the species since it varies as the young mature.

5. The effects of chlorine and heavy metals on the cultured species must be determined. If chemicals accumulate in the edible parts of the animal in excess of health or taste standards, it will be unsuitable for human consumption.

6. Every effort must be made to spawn the species in captivity since the cost of procurement of brood stock can be prohibitive. Hopefully, spawning can be induced at will so that culturing may go on year-round.

7. The diseases of each cultured species as well as cures for the diseases must be determined. The rapid spread of disease in high density rearing situations can be devastating. In addition, warm water often increases the incidence and activity of disease organisms making careful monitoring for disease necessary.

Economic Feasibility

Without a doubt one of the most important concerns when evaluating waste heat utilization concepts is economic feasibility. The factors below should be considered in the economic evaluation of commercial aquaculture facilities.

1. Selection of a species for culturing should depend on its appeal or demand in the commercial market.

2. A reliable year-round market for the products of a facility must exist.

3. High density rearing must be used to justify the cost of the facility.

4. Year-round harvesting is necessary to cover the operating cost of the facility and the high cost of food supplies.

5. The aquaculture venture must have an obvious economic advantage, when compared with sea harvesting, to be profitable.

CONCLUSIONS

The potential of waste utilization projects must be evaluated against legal constraints, utility operating requirements, biological considerations and economic feasibility.

If waste heat utilization at electric generating stations is ever to get off the ground, understanding on the part of regulators is required. Federal, state and local laws must be established with some degree of flexibility to allow an early commitment to waste heat utilization concepts in preliminary power plant designs.

Those proposing waste heat utilization facilities must become familiar with utility operating requirements. The generation of electricity must come first and any concept which interferes with that from an efficiency or economic point of view will not be acceptable to utilities.

Although LILCO views aquaculture as the most adaptable form of waste heat utilization to utility operations, we do recognize that there are many biological problems associated with the concept. For any aquaculture proposal to be acceptable certain biological considerations have to be addressed in detail at the proposal stage.

The bottom line, as in all cases, is economic feasibility. Faulty proposals for waste heat utilization facilities not only ignore utility operating constraints but in many cases fail to support the economic feasibility of the concept being put forth. This is a fatal flaw of many of the proposals being made today.

The guide word for developing an acceptable waste heat utilization concept is practicality. Will it affect compliance with applicable laws? Can it easily interface with utility operations? What is the probability of commercial success? Until an element of practicality is firmly established in this field, its future will continue to be in doubt.

UTILIZATION OF WASTE HEAT FROM NUCLEAR POWER STATION FOR COMMUNITY SPACE CONDITIONING

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SESSION IX-B
IMPACT ON WEATHER

omit

IX-B-43

Abstract

Proposals to install large power complexes at single site and to reject attendant waste heat into the atmosphere raise concern for significant atmospheric effects. A mesoscale model which was specifically designed to simulate the inadvertent modification of the atmosphere caused by localized perturbations of heat and/or moisture will be applied to a hypothetical development at a site near Baton Rouge, Louisiana. Numerical experiments will be performed to determine the relationships between local meteorological variables, orientation of cooling towers to the ambient wind, and other factors and the resultant atmospheric effects. Evaluation of the results of the model's treatment of the temperature and moisture perturbations caused by natural draft wet cooling towers will be presented. It is believed that the model can make vital and valuable contributions to the design of the facilities for disposing waste heat at large power complexes.

Title: Atmospheric Effects of Waste Heat Dissipated From Large Power Centers

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12-45-21

IX-B-45

EVAPORATIVE COOLING TOWER PLUMES:
A REVIEW OF BEHAVIOR, PREDICTIONS, AND METEOROLOGICAL EFFECTS

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ABSTRACT

In a closed cooling system, heat transfer from condenser cooling water to the atmosphere occurs either in a cooling tower or a spray pond (canals). The moisture saturated air exhausted from wet cooling towers or the spray ponds mixes with the ambient air and may form a visible cloud called a plume.

This paper reviews the various models of cooling tower plume behavior. The most frequently used model is a combination of the Buoyant Plume Rise Model and the Gaussian plume model of atmospheric dispersion. The Buoyant Plume Model provides plume altitude data. The altitude data is used in the Gaussian Model to determine water vapor concentrations.

Further, the environmental effects of waste heat and moisture plumes which are most important in the Commonwealth of Kentucky ave evaluated. Generally speaking, cooling towers and spray models will cause no atmospheric problems in Kentucky. Cooling towers in the mountainous areas of eastern Kentucky, however, have the potential of causing ground fog or snow. Cooling towers in the deeper river valleys in Kentucky could cause fogging on the valley slopes or, if a capping inversion existed over the valley, the area in the vicinity of the tower could experience ground fog.

INTRODUCTION

As the demand for electrical energy increases, an ever greater number of fossil and nuclear power plants will be constructed. Two major considerations in locating electrical generating stations are access to fuel and access to condenser cooling water. The Commonwealth of Kentucky is the leading state in coal production and has 14,000 miles of flowing water. These two factors make Kentucky a prime location for electric power plants.

Until the late 1960's, most power plants were constructed with once-through cooling. Water was pumped from a river, passed through the condenser, and returned to the river in an elevated temperature state.

In some instances, the introduction of warm water into the river has had a detrimental effect on the resident aquatic organisms. Such ecological damage from waste heat rejection is referred to as thermal pollution.

Government legislation, enforced by the U.S. Environmental Protection Agency, has restricted the use of once-through cooling. To replace this method of condenser cooling, various closed cooling systems are available. The most common closed systems in use today transfer the waste heat to the atmosphere through diffusional cooling. The Atmosphere is a much larger reservoir than the hydrosphere; atmospheric biota can tolerate a larger and more rapid change of temperature than marine life. For these reasons, the apparent environmental effect is much less with a closed system than with a once-through system.

Alteration of meteorology by cooling systems has come under extensive study since the late 1960's. Possible effects are elevated plumes, downwash fog, trapped plume fog, cumulus cloud formation (or enhancement), precipitation (snow or rain) formation (or enhancement) and icing. A major problem with assessing the possible results of cooling tower operations has been the contradictory nature of the literature. Many of the early qualitative papers predicted phenomena such as acid rain, from the combination of sulfur dioxide and cooling tower plumes, or thunderstorm generation from the thermal energy cooling towers release. Fortunately, none of the severe predictions have been found to occur. This paper will attempt to determine the state-of-the-art mathematical models, and the atmospheric effects important in the Commonwealth of Kentucky with regard to evaporative cooling tower plumes.

Cooling System Operation

The cooling systems under consideration are Mechanical Draft Evaporative Cooling Towers, Natural Draft Evaporative Cooling Towers and Spray Ponds. All devices work by passing air through a water spray. The spray droplets are cooled by removal of latent heat as water evaporates from the surface of the drop. Sensible heat removal, i.e., conduction convection and radiation, also accounts for heat loss but to a lesser degree. Spray ponds rely on natural currents for motion of the air. Mechanical Draft Cooling Towers (MDCT) use a fan to draw the air through the tower. The Natural Draft Cooling Tower (NDCT) utilizes the buoyant force of the warm moist air within the tower to provide the driving force of air motion.

Plume Formation

As environmental restrictions limit the use of once-through cooling methods, NDCT's and MDCT's are becoming the most commonly used cooling systems. Consequently, the elevated plume is the environmental alteration of greatest concern. Air that is exiting from the tower is warmer and more moist than the ambient air. Upon leaving the tower the warm moist air mixes with the cooler ambient air. Some of the vapor contained in the exhaust will condense forming a plume. The plume will rise and move downwind at a rate dependent on atmospheric conditions.

The main lifting force is the buoyancy due to the density difference between the exhaust plume and the ambient air. In MDCT's, momentum from the fan also carries the plume upward. The important factors in plume rise and plume length are wind velocity, atmospheric temperature gradient, water vapor content of the ambient air, temperature and water vapor content of the exhaust, distance from the tower, and diameter of the tower exit. As a plume rises away from the tower, it continues to mix with air and evaporates. It also disperses outward. As the concentration of droplets decreases, the plume becomes less visible. An elevated plume could pose a safety problem near an airport or an area where aircraft fly at low levels. Aside from a slight obstruction of sunlight, elevated plumes generally have no effect at ground level.

Downwash Fog

When the wind velocity is great enough (as low as 3 m/sec in one case [16], however) it is possible that downwash fog may exist. When wind blows over an obstruction such as a cooling tower; a low pressure area is created on the leeward side. The air flowing over the tower is then drawn downward. A plume rising out of the tower may be pulled down with the air. A sufficiently strong downward flow may force the plume to the ground where it causes an undesirable fogging condition.

Such a fog is usually confined to within short distances from the tower. The downward air flow quickly ceases, so that the buoyant air dominates, again lifting the plume from the ground. Air turbulence, inherent in windy conditions, causes the grounded plume to mix more rapidly in the ambient air, reducing the time of dispersion and further shortening the radius of ground fogging. Downwash fog is most common with MDCT's because they eject their vapor much closer to the ground than NDCT's.

Atmospheric Stability

In most of the literature on plume rise, the terms stable, neutral, and unstable conditions are used to describe the relation of temperature with altitude. A stable condition exists when the atmospheric temperature gradient is greater (more positive) than -0.0054°F/ft., that is, the neutral condition. This particular change is important because a plume rising in this temperature field and expanding adiabatically (no energy transfer with surroundings) would maintain a constant buoyancy with respect to the atmosphere. A step-by-step derivation of the adiabatic, atmospheric temperature gradient may be found in Perkins [38].

The unstable condition exists when the temperature gradient is more negative than -0.0054°F/ft. Plumes tend to rise further and faster in an unstable atmosphere. As the adiabically expanding plume rises, it is cooling off at -0.0054°F/ft. while the atmosphere is cooling even faster, hence the buoyancy is enhanced by the inverse dependence of air density on temperature.

Inversion Trapped Plumes

A temperature increase with respect to height, i.e., the stable atmosphere, may occur if a layer of warm air lies over a layer of cooler air. This is called a capping inversion. If a plume is negatively buoyant compared to the warm air above, it can rise no further and is trapped. If horizontal diffusion is sufficiently slow, the plume water vapor will build up. The concentration may be brought to the saturation point, and fog will form. Trapped plume vapor can also be brought to the dew point by a decrease in air temperature. This type of cooling usually occurs after sunset.

For a few hours in the early morning, the temperature may also increase with altitude as a result of the earth's surface radiating away heat quicker than the atmosphere does during night hours. Natural ground fog occurs most frequently during early morning as a result of the radiant cooling of the surface at night. Cooling tower plumes as a rule have enough lifting force to clear such an inversion.

However, spray ponds produce their vapor much closer to the ground, therefore fogging may be more of a problem. The depth of spray pond fog does not usually exceed 100 ft. but cooling towers in valleys or other confining topographies are particularly susceptible to having their plumes trapped by a capping inversion. A warm air mass over a valley combined with the valley walls acts as a container in which plume moisture could build up to form fog; this is illustrated in Figure 1.

Another type of inversion results when cool air over large bodies of water is blown inland, forcing the warm inland air mass upward. As the cool air moves away from the water and over the warmer ground, convection currents develop. A plume trapped under the inversion might be pulled to the ground in the convection currents. This type of inversion usually reaches only a few hundred yards inland from the body of water. Figure 2 demonstrates the occurrence of this type of inversion. The existence of an inversion does not assure plume trapping. The plume's buoyancy and/or its momentum may be enough to carry it past the inversion. NDCT's, with heights of 300 to 500 feet, release their plumes above most low level inversions. The high exhaust velocity of MDCT's frequently enable their plumes to pass through low level inversions by virtue of their momentum.

Other Meteorological Effects

Formation or enhancement of cumulus or stratus clouds may result from the operation of cooling towers. For cumulus cloud formation, a period of unstable air with a light wind present is favorable. The wind could then spread the cloud cover over a wide area. Formation of rain and snow from cooling tower generated clouds or plumes had been reported but accumulations have been small [3]. Natural rain or snow could be increased by passage through a plume; however, no occurrences were reported in the literature.

On a day when air and ground temperatures are below freezing, a plume that intersects the ground could deposit ice. Most ice formation has been confined to the immediate cooling tower area.

ANALYTICAL METHODS OF PLUME BEHAVIOR PREDICTION

Most of the analytical methods used to predict moist cooling tower plume behavior have grown from mathematical models developed for dry smokestack plumes. The radius of cooling tower plumes, both mechanical and natural draft, are considerably larger than the radius of smoke stack plumes. The exhaust oriface diameter on a Mechanical Draft Tower, which may have 15-25 contiguous cells, is on the order of 30 feet; for a Natural Draft Tower, it is much larger, about 300 feet; an average power plant smoke stack diameter is about 20 feet.

Empirical Plume Rise Equations

Briggs [5] summarized a number of dry plume rise equations for varying atmospheric conditions. These equations can be modified for wet plumes by using Hanna's [15] flux buoyancy factor.

$$\Delta H = 2.3\left[\frac{F}{US}\right]^{1/3} \tag{Eq. 1}$$

Stable or near neutral conditions

$$\Delta H = 1.6\,\frac{F^{1/2}\,x^{2/3}}{U} \tag{Eq. 2}$$

$$\Delta H = 150\,\frac{F}{U^3} \tag{Eq. 3}$$

Unstable and neutral conditions

$$\Delta H = \frac{5.0\,F^{1/4}}{S^{3/8}} \tag{Eq. 4}$$

Stable and Calm (no wind) conditions

ΔH = rise of the plume above the tower
F = flux buoyancy factor
U = wind velocity
x = down wind distance

where atmospheric stability is

$$S = \frac{g}{t_{eo}}\left(\frac{dT}{dz} + 0.0054\ °F/ft\right) \qquad \text{(Eq. 5)}$$

Hanna's flux buoyancy factor (F) is

$$F = W_o g R_o^2 \left[1 - \frac{T_{eo}}{T_{po}} + 0.61(q_{po} - q_{eo}) + \frac{L}{C_p T_{po}}\right] \qquad \text{(Eq. 6)}$$

where
W_o = tower exit velocity of plume
g = gravitational acceleration
R_o = tower exhaust radius
T_{eo} = environmental temperature (°R or °K)
T_{po} = plume initial temperature (°R or °K)
q_{eo} = environmental mixing ratio (gm H_2O)/gm Air
q_{po} = plume initial mixing ratio (gm H_2O)/gm Air
L = Latent heat of vaporization of H_2O
C_p = Specific heat of air at constant pressure
U = Wind velocity, and
$\frac{dT}{dz}$ = Altitude temperature gradient

Values of q_{eo} and q_{po} may be found in Hanna [20].

Buoyant Plume Model

Another approach to plume rise is the Buoyant Plume Rise Model found in Slawson [41]. This model uses the governing momentum, mass, and energy conservation equations as the basis of its derivation. To keep the final equations analytically solvable, it was necessary to assume that the moisture concentration within the plume was uniform in the radial direction. The vapor content, in reality decreases with radius. It was also assumed that atmospheric density did not change along the plumes length. These assumptions lead to two equations for plume radius. The first, Equation 7, is a function of downwind distance and is applicable only in the fully bent-over region (plume traveling parallel to the ground). The second, Equation 8, is a function of altitude and can be used over the full length of the plume.

$$R^3 = 3\alpha\left[\frac{\ell_b x^2}{2} + \ell_m^2 x\right] + R_o^3 \qquad \text{(Eq. 7)}$$

$$R = \alpha z + R_o \qquad \text{(Eq. 8)}$$

where
$\ell_b = F_o / U^3$

$F_o = \frac{g Q_o}{\pi \rho_g C_p T_a}$

$\ell_m = R_o W_o / U$

R_o = tower exhaust radius
g = gravitational acceleration
Q_o = heat flux at tower exit
ρ_s = effluent density
C_p = specific heat of air at constant pressure
α = entrainment constant, and
W_o = tower exhaust velocity

If R_o is set equal to zero, the cooling tower being modeled becomes a point source. Then Equations 7 and 8 are combined yielding a plume rise equation:

$$z = \Delta H = \left(\frac{3}{\alpha^2}\right)^{1/3} \left(\frac{\ell_b x^2}{2}\right)^{1/3} = \left(\frac{1.5}{\alpha^2}\right)^{1/3} \frac{F_o^{1/3} x^{2/3}}{U} \qquad \text{(Eq. 9)}$$

which is similar to Brigg's previous Equation 2 for plume rise. The entrainment constant, α, is am empirical constant since no analytical theory for air mixing with the plume exists.

Modeling Problems

The myriad of factors that influence plume rise prevents any single model from being all encompassing. Certain parameters may be difficult to measure or may vary with height or downwind distance. Atmospheric parameters that vary with height, such as wind velocity, temperature and water vapor content, must be fitted to an equation; otherwise, an average value must be used.

Water Vapor Concentration

After a plume has reached its maximum height, calculations of water-vapor concentrations are done using the Gaussian Plume Model of atmospheric dispersion. Extensive application of the method's application appear in Perkins [38] and Turner [47]. The general equation that yields concentrations (mass/volume) is

$$\chi(x,y,z,H) = \frac{Q}{2\pi\sigma_z\sigma_y U} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_z}\right)^2\right] \left[\exp\left(-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2 + \exp\left(-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right)\right] \qquad \text{(Eq. 10)}$$

For ground level concentration (z = 0) the equation becomes

$$\chi(x,y,0,H) = \frac{Q}{\pi\sigma_z\sigma_y U} \exp - \frac{1}{2}\left[\left(\frac{y}{\sigma_y}\right)^2 - \left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(Eq. 11)}$$

For ground level concentrations, directly below the plume center line ($y = 0$, $z = 0$) the equation further simplifies to

$$\chi(x,0,0,H) = \frac{Q}{\pi\sigma_y\sigma_z U} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{(Eq. 12)}$$

The vapor density on the plume center line is

$$\chi(x,0,H,H) = \frac{Q}{\pi\sigma_y\sigma_z U}\left[1 + \exp\left[-2\left(\frac{H}{\sigma_z}\right)^2\right]\right] \qquad \text{(Eq. 13)}$$

where

Q = vapor flux rate (mass/time)
σ_z and σ_y = plume standard deviations (length) (these are a function of downwind distance and of atmospheric stability)
U = horizontal wind velocity
H = height of plume rise plus height of cooling tower.

Graphs of σ_z and σ_y as a function of downwind distance are presented in Turner [47]. Each graph has six different lines; each line (labeled A-F) represents a class of atmospheric stability. The atmospheric stability is determined qualitatively by knowing the average wind velocity and the amount of incoming solar radiation. The two items are cross referenced on a chart given in Turner [47] thus yielding the stability class letter.

Multi-Source Plumes

Mechanical Draft Cooling Towers for large power plants are commonly constructed in a line of fifteen to twenty-five cells. The plumes of the individual cells combine to form a single larger plume that entrains air at a slower rate, therefore maintaining the plumes buoyancy for a longer time. As a result, the plume rises to a greater height.

Wilson [49] presents an equation to account for the effect of multi-towers on plume rise:

$$\Delta H = \left(\frac{N + S}{S + 1}\right)^{1/3} \Delta H \qquad \text{(Eq. 14)}$$

where

$$s = 6 \left(\frac{L}{N^{1/3}\ \Delta H}\right)^{3/2} \qquad \text{(Eq. 15)}$$

N = number of cells
ΔH = plume rise for a single cell
L = length of cooling tower line

Concerning the Marble Hill Generating Station, Public Service of Indiana [30] (P.S.I.) altered the Gaussian Plume Model to take into account emission from a finite line source with wind blowing at a right angle to the long axis. For ground level concentrations on the center line of a finite line source, the equation is

$$\chi(x,0,0,H) = \frac{Q\sqrt{2}}{\sqrt{\pi}\ \sigma_z L} \exp - \frac{1}{2} \left(\frac{H}{\sigma_z}\right)^2 \operatorname{erf} \frac{L}{2\sqrt{2}\ \sigma_z} \qquad \text{(Eq. 16)}$$

where all symbols are defined as before.

Downwash Model

P.S.I. has also presented a model for cooling tower downwash. Downwash occurs when the plume is drawn into the low pressure area on the downwind side of the tower. It can then be assumed that the plume center line intersects the ground.

The water vapor equation then becomes

$$\chi(x,0,0,0) = \frac{Q}{\pi \sigma_y \sigma_z U} \qquad \text{(Eq. 17)}$$

However, air turbulence along the ground from nearby large structures (in this case the reactor containment building) is sometimes important in dispersing the grounded plume. The turbulent wake is included in the concentration equation through a dispersing factor D_b. Then

$$\chi\text{wake} = \chi\text{no wake}/D_b$$

where

$$D_b = 1 + \frac{CA}{\pi \sigma_z \sigma_y}$$

A = reactor building minimum cross section (2700 m^2 for Marble Hill units 1 and 2)

C = empirical building shape factor (0.5 for Marble Hill units 1 and 2)

Plume Length and Fog Prediction

Once airborne or ground level concentrations of water vapor are known, they are combined with ambient temperatures through a psychrometric chart or an empirical equation to determine either the point at which the visible plume will disappear or the point at which ground fog will be formed.

Plume Modeling for Environmental Reports

The preceding calculational methods for ground fog and visible plumes are used extensively in environmental reports for both nuclear and fossil fuel power plants. Weather data at a proposed site is collected over a period of one year. Fog and plume calculations are then carried out for the different weather conditions that occur over the period of that year. The resulting frequency of visible plumes or ground fog are placed on a site map and are represented by an isopleth, i.e., lines joining points of constant occurrence, see Figure 3.

Summary of Evaporative Cooling Tower Plume Predictions

All power plant environmental reports reviewed use some form of the Briggs equations [5] for plume rise and the Gaussian Plume Dispersion Model for concentrations. Each of the consulting environmental engineering firms altered the empirical constants or boundary conditions slightly for a given plant site. Those models are also used by the United States Nuclear Regulatory Commission (N.R.C.) and United States Environmental Protection Agency (E.P.A.) in their review work.

The advantage of the Gaussian Plume Model is its ease of application; also under certain conditions, it produces results that are the same as or superior to more complicated models. The major drawback is that before the plume reaches its maximum height the only place the dispersion equation gives realistic results is on the plume's centerline. McVehil [33] conducted a survey of analytical plume prediction methods and reached the following conclusions:

a) No model is adequately validated by field measurements for a variety of tower types and meteorological conditions.
b) The accuracy of the best models varies by as much as 25 percent from observed plumes.
c) All models must be "tuned" (have empirical constants adjusted) for a specific tower.
d) No model shows an ability to predict fog and other meteorological effects.

PLUME EFFECTS IN THE KENTUCKY ENVIRONMENT

As the population in the Midwest increases the demand for electricity will also increase. To meet this demand more electrical generating stations are being constructed and are in the planning stages. A major consideration in locating a power plant is access to condenser cooling water. In the Commonwealth of Kentucky, rivers supply the vast majority of cooling water. Until recently the cooling water was pumped from the river through condensing units and discharged back into the river. In the late 1960's, concern began to develop over the ecological damage to the waterways from the massive introduction of water in an elevated temperature state.

Government regulations soon followed and limited the thermal effluent that could be disposed of in the rivers. Power plants constructed after the legislation have used closed cycle systems for heat rejection. The heat sink these systems use is the atmosphere instead of the hydrosphere. The closed cycle systems presently available include cooling lakes, spray ponds, spray canals, dry cooling towers, wet/dry cooling towers, and wet cooling towers. All but the cooling towers require a large land area for installation. All closed systems are more expensive than once-through cooling; however, wet cooling towers in general are the least expensive of the closed systems. Expense and land area factors are responsible for wet cooling towers being the most widely used closed cooling system. The two types of wet cooling towers, Natural Draft and Mechanical Draft, transfer most of their heat to the atmosphere through evaporation of water.

Information Sources

Information on plumes and meteorological effects specifically for Kentucky or bordering states is very limited. Most data available comes from the Ohio Valley east of Louisville. The main sources of materials related to plumes have been environmental reports prepared by government agencies and direct correspondence with the electric power companies. The environmental reports, of which there are four, were all for proposed power stations along the Ohio River. Two of the power stations are nuclear, one of which has a natural draft cooling tower and the other has two banks of mechanical draft cooling towers. The two other stations are coal-fired and both will have mechanical draft cooling towers.

Eastern Kentucky

The first NDCT constructed in the United States was constructed at the Big Sandy Power Station in Eastern Kentucky. No plume study has been conducted at Big Sandy. The American Electric Power Service Cooperation (AEPS), which owns Big Sandy, has studied plume behavior at its John E. Amos [3] power plant in Charleston, West Virginia. AEP feels that general meteorological conditions are the same at both plants, so data results from John E. Amos can be applied to Big Sandy. Big Sandy lies in an area where approximately 30 days of natural fog occur per year. The AEP study showed that plumes from NDCT's rise above natural ground fog and do not contribute to it. The highest wind speed recorded in the John E. Amos study was 45 mph. At this wind speed, no plume downwash was reported. On days when conditions for the formation of natural clouds were favorable, the cooling tower effluent often generated isolated clouds. The AEP study reported that on ten occasions when the temperature was below 10°F, light snow fell from the plume and reached the ground at distances of over five miles from the tower. The largest reported accumulation was one inch [3]. Most plumes rose from 2000 to 6000 feet above grade. The longest recorded plume was 9 miles.

Western Kentucky

The plume report for the Paradise Steam Plant [41] (Tennessee Valley Authority) contains no information on general meteorological effects. The TVA report concentrated on plume formation theory and compared field measurements with theoretical predictions. The largest plume cited in the report occurred with all three NDCT's operating. The top of the plume extended to an altitude of 3/4 mile. The plume length was 3 miles.

Kentucky Plume Models

Most power plant environmental statements have sections devoted to the atmospheric effects of the projected cooling system and of the alternate systems considered. The meteorological plume effects predicted in environmental statements are determined through the use of computer models incorporating the plume rise and dispersion equations discussed earlier. The models are constructed so as to be conservative, that is, forecast meteorological consequences with conditions that would cause the worst possible effects.

Terrain Effects

Three of the projected power stations, whose impact statements were reviewed, are located on the Ohio River flood plain and have high ground surrounding them. This is briefly taken into consideration in the Spurlock Station [17] model only. In the Spurlock model, if the height of the terrain around the station is the same as the plume rise of the MDCT's at that location, fog is assumed to occur. The capping inversion fog previously mentioned was not considered in the East Bend [15], Spurlock [17], and Zimmer [18] environmental reports. If this condition occurred, road, river and rail traffic in the area could be effected. In the case of the Zimmer Nuclear Generating Station, the top of its NDCT (479 feet above grade) is 250 feet above the top of the surrounding terrain. This would most likely prevent the station's plume from being trapped and fogging the valley. East Bend and Spurlock have MDCT's and exhaust their vapor well below the valley rim. Both stations are coal-fired, and the combustion produced particulates in the air would further increase the possibility of valley fog.

The Marble Hill [16] Nuclear Generating Station will be constructed on the top of the valley rim so its MDCT's should not cause any problems in the river valley below.

The Power Plants

East Bend Units 1 and 2 in Boone County, Kentucky, will be a 1200 MWe generating station. Its MDCT's will evaporate 6,200 gpm in the cooling process. The computer analysis projects a maximum of 40 hours per year of fog in the northeast portion of the site.

Marble Hill Nuclear Generating Station units 1 and 2 will produce 2360 MWe and will be located in Jefferson County, Indiana, adjacent to Trimble County, Kentucky. Marble Hill's MDCT's will evaporate 27,000 gpm at maximum power output. A total of 92 hours/year of fog are projected at a 2000 ft. radius for all compass directions around the site.

The Spurlock Station units 1 and 2 is an 800 MWe coal-fired power plant located in Mason County, Kentucky. The plant's MDCT's will evaporate a total of 8,530 gpm of water and will produce a possible extra 30 hours/year of fog.

The Wm. H. Zimmer Nuclear Generating Station will generate 840 MWe. The plant is located in Clermont County, Ohio, across the Ohio River from Pendleton County, Kentucky. Zimmer's NDCT will release 12,000 gpm to the environment with a projected 25 days/year of ground fog resulting.

The fogging frequencies presented were computed using similar models over geographical regions where weather conditions were nearly the same for all plants and where topographic effects were not dominant. The one remaining important factor is vapor flow rate, yet the occurences of fog do not appear to vary according to the tower effluent rate. The reason for this is not clear. The conclusion of the environmental reports is that none of the four proposed stations will cause unacceptable meteorological alterations. This conclusion was reinforced through contact with personnel at Kentucky Utilities Company's Ghent Generating Station and Cincinnati Gas and Electric Company's Miami Fort Generating Station which indicated that cooling operation has produced no adverse atmospheric phenomenon. These two plants are on or near the Ohio River.

General Siting Considerations

The locations where cooling tower operation is most likely to cause problems are areas where natural fog occurs frequently or the topography could trap moisture laden air. The mountainous area of Eastern Kentucky (bordering Virginia) has the highest incidence of natural fog in the state. A proposed cooling tower site should receive close scrutiny before construction is undertaken in this region. Some of the deeper river valleys in Kentucky are poor locations for cooling towers because of their limited ventilation and humid climate. With the exception of the two types of locations mentioned, cooling tower siting should not pose a problem in Kentucky.

RESEARCH NEEDS

Despite the great amount of material that has appeared on the environmental effects of evaporative cooling towers, very little field data has been collected. Only four quantitative field studies of plume behavior have been conducted at this time; they are Slawon [41], Kramer [28], Meyer [32], and Hanna [20]. Three studies were performed at electric power generating stations. The fourth was conducted at the Oak Ridge Gaseous Diffusion Plant. The instrumentation needed to measure ambient and plume data includes anemometers, thermometers, hygrometers, cameras and transits. Much of the data has to be taken at regular altitude intervals; therefore, aircraft or weather balloons must be used. The period of data collection should extend for a year or longer.

Most theoretical models used in preparing environmental reports have not been calibrated against operational cooling towers, nor has any study been conducted to determine how accurately pre-construction simulation predicts the actual operating atmospheric effects.

An alternate method to predict plume behavior would be to use scale models in a wind tunnel or water flume. Some limited work has been done on cooling tower modeling; however, most of this has been in Europe [4,50]. More extensive wind tunnel and flume modeling has been done for smoke stacks in the United States. The smoke stack studies could serve as a basis for cooling tower simulation.

Another phenomena that has received little attention in the literature is the possibility of thunderstorm and tornado formation. At the present the energy released by most cooling systems is insufficient to create severe weather. In the future, if large numbers of cooling systems are constructed in a confined area, e.g., energy parks, the potential may exist for harmful weather modification.

Equipment Required for Atmospheric Heat Rejection and Plume Studies

For phase heat transfer devices, dry bulb and dew point temperatures are extremely important in determining cooling performance and characteristics of vapor plume formation. Measurements of such data require micro-bead thermistors, hygrometers, and psychrometers. Other data necessary for cooling tower studies are wind speed and direction, SO_2 concentration, size and concentration of suspended particulates, air pressure and solar radiation intensity. Instruments to measure these parameters are an SO_2 analyzer, dust counter, anemometer, barometer and solar radiation detector.

For plume studies cameras and transits would also be required to record plume appearance and length. A major question that is still unanswered is, "When does a plume become visible?" Therefore, besides the need to know water vapor concentrations in a plume, the water droplet concentration and spectrum must also be determined. Methods of droplet detection range from impressions on sensitive paper to scatter or imaging with laser light.

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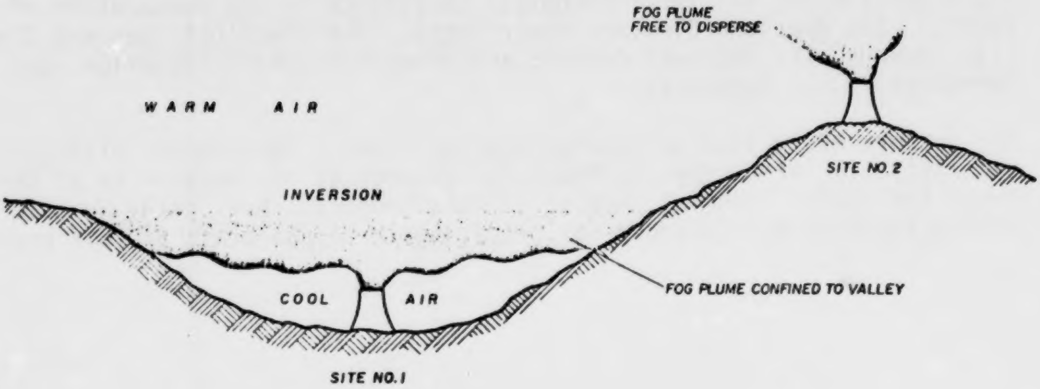

FOG PLUME FREE TO DISPERSE
WARM AIR
SITE NO. 2
INVERSION
COOL AIR
FOG PLUME CONFINED TO VALLEY
SITE NO. 1

Figure 1: Valley Induced Fog
(Taken from DeHarpporte, Ref. [14])

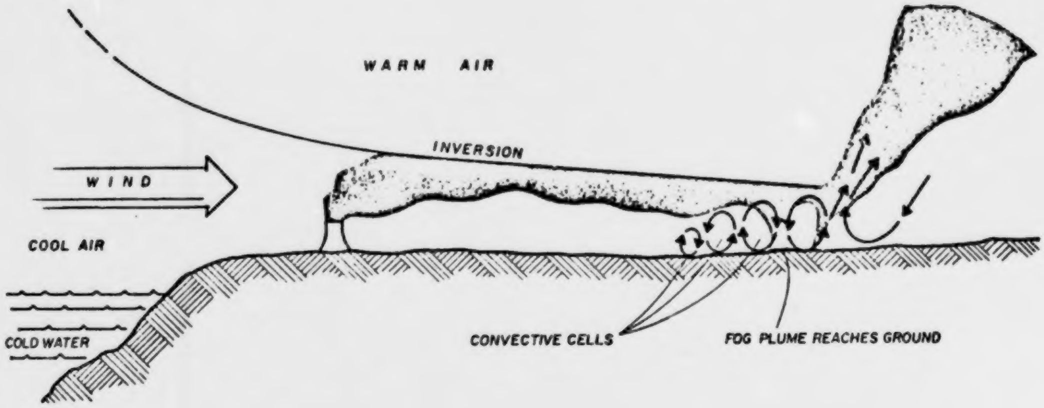
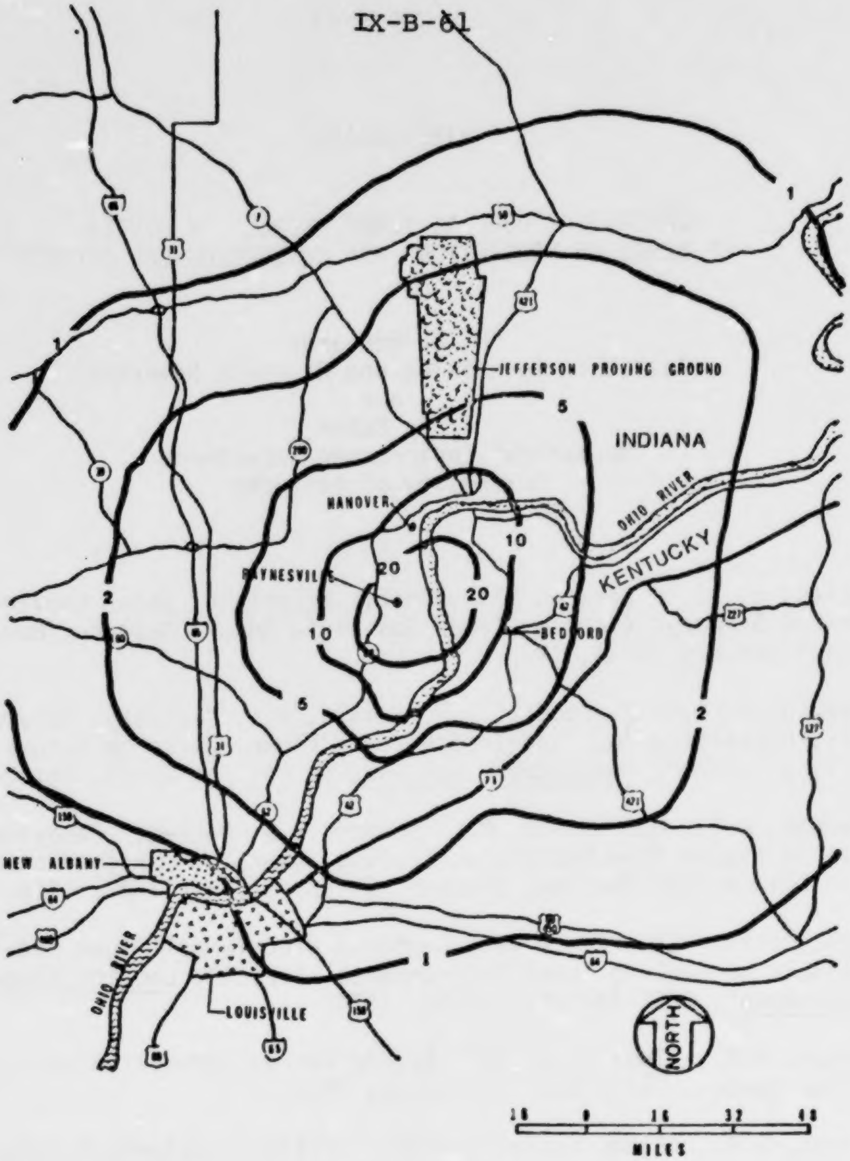

WARM AIR
INVERSION
WIND
COOL AIR
COLD WATER
CONVECTIVE CELLS
FOG PLUME REACHES GROUND

Figure 2: A Typical Trapped Plume
(Taken from DeHarpporte, Ref. [14])


JEFFERSON PROVING GROUND
INDIANA
KENTUCKY
OHIO RIVER
HANOVER
PAYNESVILLE
BEDFORD
NEW ALBANY
LOUISVILLE
OHIO RIVER
1
2
5
10
20
20
10
5
2
1
NORTH
16 0 16 32 48
MILES

MARBLE HILL NUCLEAR GENERATING STATION - UNITS 1 & 2
ENVIRONMENTAL REPORT – CONSTRUCTION PERMIT STAGE

Figure 3
CONTOURS OF ELEVATED VISIBLE PLUME HOURS/YEAR - UPPER BOUND
(Taken from Ref. [30])

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IX-B-67

A NUMERICAL MODELING STUDY OF WASTE HEAT EFFECTS ON SEVERE WEATHER

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ABSTRACT

A two-dimensional, time-dependent model has been developed which gives realistic simulations of many severe storm processes -- such as heavy rains, hail, and strong winds. The model is a set of partial differential equations describing time changes of momentum, energy, and mass (air and various water substances such as water vapor, cloud liquid, cloud ice, rainwater, and hail). In addition, appropriate boundary and initial conditions (taken from weather sounding data) are imposed on a domain approximately 20 km high by 20 km wide with 200 m grid intervals to complete the model.

The U. S. Nuclear Regulatory Commission is supporting work with this model to test the effects on severe storm simulations of adding vapor and heat at the lower grid points of the model. The amount of heat and vapor added will be varied to simulate various configurations of cooling tower complexes and the results compared to runs with the model when no additions are made. Quantitative assessments of the effects of various cooling tower waste heat rates in a few local weather conditions will be made by the end of the research period, October 1978.

1. INTRODUCTION

The purpose of this paper is to present a numerical cloud model capable of simulating certain types of severe storms, those having heavy rains, hail, and possible high winds, but excluding tornadoes. In addition, discussion will be made of the modifications of the model that will allow the simulation of excess water vapor and heat expected from various cooling tower complexes.

2. RATIONALE FOR THE STUDY

2.1 Power Development

Development and utilization of the low sulfur coal reserves in the northern Great Plains states of Montana, Wyoming, North and South Dakota, and Nebraska are already well underway [1], [2], [3], [4], [5], [6], [7], [8], [9]. According to projections made by the Environmental Protection Agency in their recent Northern Great Plains Resource Program (NGPRP), coal production in the northern Great Plains will rise from 50,000,000 tons in 1975 to over 350,000,000 tons by the year 2000. Current plans for fossil fuel development in this area include utilization of the coal by export (including a proposed coal slurry pipeline), gasification and power generation at mine-mouth or at sites providing easy access to the coal supplies.

Climatological and physical studies in this country and abroad have shown that urban complexes often produce changes in rainfall patterns, and hail and thunderstorm frequency, overhead and downwind from the effluent sources. Thus far, however, no comprehensive investigations have been undertaken to document the impacts from energy development alone, which may show interaction of effluents with dynamical and physiochemical processes of the atmosphere bringing about inadvertent changes in local weather.

2.2 Weather in the Plains

The local weather in the spring and summer in this region is often characterized by severe thunderstorms which produce hail, flash floods in the mountainous regions, tornadoes or strong straight winds. The maximum frequency of hail in the United States occurs near Cheyenne, Wyoming. Flash floods of devasting proportion have occurred in 1972 in Rapid City and in 1976 in the Big Thompson Canyon area. The damage to property and life is considerable, hundreds of lives lost, and hundreds of millions of dollars damage in the flash floods. Hail alone causes over fifty million dollars of crop damage annually in South Dakota.

No one has suggested that cooling tower effluents contribute to such disasters. However, some local citizens in the Rapid City area blamed local cloud seeding efforts using finely powdered salt for the Rapid City flood, although the scientific evidence showed no effect [10], [11]. The effluent from cooling towers may be more effective than the finely powdered salt commonly used to affect the coalescence process for rain formation. Consequently, the same citizen misunderstanding that occurred with cloud seeding and natural disasters can be expected to surface with regard to cooling tower effluents and natural disasters. Thus, it seems prudent to check the effects of the effluents on severe weather in whatever ways possible — numerical simulations and observations, if possible, to determine what effects to expect.

2.3 Characteristics of Convective Clouds and Power Plant Effluents

Convective clouds are characterized by substantial upward motions set off by atmospheric instability. The primary cells of a storm have dimensions of 1 km to several tens of km wide and reach several km's high. The vapor flux (gm of water vapor per second) into a small cumulus is about 10^7 gm sec^{-1}; into a giant hailstorm, 10^9 to 10^{10} gm sec^{-1}. The cloud or cell lifetime varies from 10 to 20 minutes, the storm an hour or more, so that a typical Great Plains thunderstorm produces a few hundred to a few thousand acre feet* of water on the ground.

The output of cooling towers is small in comparison with the numbers above. The source width of natural draft towers covers 60 m with a vapor flux of approximately 10^6 gm sec^{-1} in liquid and vapor form from a complex of 3 or 4 towers. However, the plume has characteristics of a small cumulus [12] so that droplets of 60 μm to 100 μm diameter occur. These are very efficient raindrop embryos and can be expected to enhance the coalescence process of rain formation in the larger clouds ingesting the cooling tower plumes.

2.4 Hypothetical Effects of Cooling Tower Effluents on Clouds

At least four effects of power plant effluents on the atmosphere can be hypothesized:

1. Water vapor and heat increase convective instability.
2. Water vapor provides fuel for cloud and fog formation and precipitation evolution.
3. Cooling tower plumes provide "precipitation embryos" for preexisting clouds.
4. Smoke stacks and, to a lesser extent, cooling towers provide particulates that may act as condensation nuclei (CCN) and ice nuclei (IN) to augment and modify the natural nuclei content.

The atmospheric reaction to the four effects mentioned above will be different depending on the season of the year and even the time of the day. For example, the small increase in convective instability will have little influence on the stability of the winter atmosphere compared to the more unstable summer conditions. However, the addition of moisture to the cold, crisp December air will result in extensive plume formation and possible local light snow, whereas the same emissions in the summer may be mixed rapidly and turbulently and result in minimal visible plume formation. This dispersion will normally be more effective in unstable afternoon conditions.

In addition, the type of cooling tower will influence the effects to be expected. Natural draft towers, 150 m tall, push their moisture and heat high into the atmosphere -- no ground fog has been reported from such devices. Shorter mechanical forced draft towers (17 m high) are more likely to cause ground fog and icing. The cumulative effect of several power plants dispersed over a region will be more difficult to detect

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*One acre foot equals 1.23 x 10^6 kg equals 1.23 kilotons of water.

than the local effects of individual power plants. Nevertheless, there are certain weather situations which may enhance the effects of multiple power plants. Strong convective situations are controlled by mesoscale convergence (of order 10^{-4} $\sec^{-1}$ or greater), [13]. This convergence tends to concentrate the vapor (and particulates) in a region which fuels the convective storms. In winter storms, similar processes work to moisten the lower atmosphere and lead to efficient snowstorms. The vapor released from the numerous power plants in a region may then serve to help produce the rain or hail from a convective system (a squall line) or the snow from a cyclonic system.

It has been suggested in a report to Congress in 1976 on Nuclear Energy Centers (NEC) that

> The combination of the NEC inputs with properties of the atmosphere can cause convective activity to occur earlier in time, to occur at different locations, to develop convective clouds on occasions when convective clouds would otherwise not occur, and to perhaps increase the violence associated with major thunderstorms. Some meteorologists have suggested that starting more convection, and starting it earlier, may reduce the number of very large thunderstorms that are formed. The possibility of this and the spacing of the heat rejection systems to do this are unknowns and require extensive further study.

Concerning the third effect listed above, Hosler [12] reporting on flights in cooling tower plumes concluded that "the liquid water content, drop size distribution, and air motions are almost identical in the plume and in small cumulus clouds." His measurements showed drops of 60 μm to 100 μm diameter and maximum liquid water contents of 1 gm m^{-3}. Most water contents were a few tenths of a gm m^{-3}. This means that the cooling tower plumes would be supplying to the base of clouds ready-made precipitation embryos that would enhance the coalescence process of rain formation. Cloud seeding field experiments in this region of the country, [14], [15] have shown that seeding clouds 1000 ft below their base with 100 to 200 kg of finely powdered salt can induce rain showers. The hygroscopic salt particles triple their size (increase their water mass by a factor of 27) by the time they enter the cloud base and provide efficient raindrop embryos; i.e., large particles which will grow by colliding and coalescing with smaller cloud droplets. The cooling tower plumes from plants producing 1000 to 2000 MWe may add more liquid in greater size droplets than the salt seeding experiments. Approximately 1.7 million kg of water, much of it condensed depending on atmospheric conditions, will enter the cloud base in a 30-minute period. If only 1/1000 of this were condensed, this still represents 1700 kg of liquid droplets entering the cloud. A large coalescence seeding effect may then be expected.

The fourth effect mentioned above concerning CCN and IN additions to the atmosphere is not directly attacked with the type of cloud model to be

discussed below. However, much fine work is progressing in that area in both observations and numerical simulations.

2.5 Numerical Modeling as a Partial Solution

Numerical simulation of realistic situations offers a partial solution to determining the effects of power plants on the atmosphere. The numerical cloud model must treat the various dynamic and microphysical processes in enough detail to provide a reasonable estimate of what would occur if the cooling towers were not there. The model should be tested in various situations and compared with radar, aircraft, and ground observations. Favorable comparison with every minute detail of a storm is probably not possible, but at least the general convective characteristics and the primary precipitation processes should be detected.

Numerical simulations of a reasonable size region require grid spacings of 100 m or more, a value greater than the dimensions of a single cooling tower (a natural draft tower or a bank of mechanical draft towers). Consequently the vapor and heat output from several towers are assumed to be mixed uniformly in the lower boundary layer, and a source term appropriate to the averaged output added to the heat and vapor equations at a few lower boundary grid points.

The applicability of the results to other geographic regions must be made with caution. It is much safer to run the models with soundings from various portions of the country and with the parameterized precipitation microphysics that are applicable to a particular region. For example, the cloud droplet concentration and distribution breadth are very different in Great Plains thunderstorms and subtropical thunderstorms, which would result in different rates of precipitation formation in the two regions.

The complete solution to the problem will only come about after observations are tied in with the numerical simulations so that a general understanding of the physical processes occurring is accomplished.

3. A NUMERICAL CLOUD MODEL

A cloud model has been developed which has been successful in simulating many features of severe storms and which is being modified to test the effects of cooling tower vapor and heat emissions on the atmosphere. The model is a two-dimensional, time-dependent numerical model of cumulus growth over mountains [16], [17], [18], [19], [20], [21]. The hail process is included so that a class of severe storms can be simulated. In addition, the model includes the effects of mesoscale convergence via the initial and boundary conditions [22]; and thus, it can be used to check the speculations of power park effects on severe storm conditions in conditions of strong mesoscale convergence.

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The model has 200 m grid spacings covering a 19.2 km x 19.2 km area in the X-Z plane. Atmospheric wind, potential temperature, water vapor, cloud liquid, rain, cloud ice, and precipitating ice (hail) are the primary dependent variables. Extension of the model to deep convection has been made utilizing a density weighted stream function. A set of nonlinear partial differential equations constitutes the model. These equations include the first and third equations of motion, a thermodynamic energy equation, and water conservation equations for the three phases of water. Production of cloud water and ice, rain, and precipitating ice are simulated. Equations using the ideas of Kessler [23], and Berry [24], provide for the production of rain from cloud water. The rain is assumed to have a Marshall-Palmer size distribution. Precipitating ice is formed by freezing rain to ice by means of an equation due to Bigg [25]. In addition, an approximation to the Bergeron-Findeisen process is simulated to transform some cloud water to the precipitating ice content. Further growth is controlled by equations for wet and dry growth of hail [26]. An exponential size distribution, different than that for rain, is assumed for the precipitating ice which is consistent with observations by Federer and Waldvogel [27] and Battan [28]. Cloud water is frozen to cloud ice isobarically at a predetermined temperature with an equation developed by Saunders [29]. Only rain and its frozen counterpart can precipitate. Cloud liquid and cloud ice travel with the airflow. Evaporation of all forms of cloud particles can occur. Melting of the frozen precipitation is also simulated. The equations are integrated with respect to time on a two-dimensional grid.

Horizontal gradients of the variables at the inflow and outflow boundaries are set equal to zero. At the top boundary, all variables are held constant. Evaporation and heating rates at the earth's surface are assumed and diffused into the lowest grid points, located 10 m above the surface, changing the entropy and water vapor fields [16]. These changes at the lower boundary are advected and diffused into the surrounding grid points and eventually lead to thermals which then produce clouds, if the initial atmospheric sounding is unstable enough. Cloud shadow effects are simulated via Liu and Orville [17]. Cloud substance is not permitted to form at the lowest grid points, but precipitation can fall through this level, and that which does is accumulated to give a predicted depth of rain or hail on the ground.

The model has been modified to accept data from a radiosonde sounding as initial conditions for temperature, humidity, and pressure heights. In addition, the horizontal wind in the direction of motion of the storm is used in a modified form. The speeds are reduced to allow the storms to remain in the domain of integration longer and to compensate for the exaggerated effect of vertical wind shear in two-dimensional models. This last comment refers to the fact that two-dimensional models do not allow airflow around the middle levels of an active convective cloud, but instead tend to inhibit convection which protrudes into high wind shear regions. Normally a decrease to 20% of the wind speeds projected onto a two-dimensional "storm motion" plane is used for the wind speeds.

The equations are solved using Crowley [30] - Leith advection techniques. Following Marchuk and Leith, a two-step advection scheme is used — the horizontal advection calculated first; the vertical advection second.

The scheme is of first order accuracy in time, second order in space. Direct methods [31] for an irregular grid are used to solve the Poisson-type equation for the stream function. The diffusion terms are represented in the standard fashion, substituting the second order approximation for the ∇^2 term and the nonlinear values for K as described in Drake et al., [32]. Tests of the model using 50 m and 100 m grid intervals have been run in the past and reported elsewhere [33], [34]. Comparisons with observations are being done and are encouraging [21].

4. EXAMPLE OF A SEVERE STORM SIMULATION

Two types of solutions are occurring in the model results [21]. One is more cellular in nature and represents a "turning over" of the atmosphere to a more stable state from an initially unstable condition. The other is characterized by winds of opposite direction in the lower and upper atmosphere and by the formation of a large convective cell of the dimensions of the grid domain, upon which smaller perturbations are superimposed. These perturbations travel up a sloping updraft and periodically (every 10 to 15 min) intensify the storm. A gust front forms and moves off the grid, after which the convection dies out.

An example of the second form of numerical result is shown in Fig. 1(a-h) and a conceptual model of a similar storm taken from observations [35] is shown in Fig. 2.

Items such as the sloping updraft, rounded dome top, radar overhang (not shown), and pedestal and shelf clouds are all features of both the numerical simulation and the observations. Deficiencies of the model include the echo weak vault in the radar echo patterns, the cloud top height (about 1 km too low in the simulation) and the occurrence of strong inflow from the rear. A movie of the simulation has been made and will be shown at the conference.

These and other results of comparisons with observations have led us to be encouraged that the general convective characteristics and primary precipitation processes on a particular day may be detected in numerical simulations. Consequently the model should serve as an aid in predicting the effects of vapor and heat additions to the lower atmosphere on severe convective days.

5. MODIFICATIONS OF THE CLOUD MODEL TO SIMULATE WASTE HEAT ADDITIONS TO THE ATMOSPHERE

The technique to be used is to add a source term for heat and moisture into the appropriate equations at several grid points in the lower atmosphere of the model. These terms must be of the proper size to simulate accurately the moistening rate of a complex of cooling towers, perhaps a power park (composed of 40 - 1000 MWe cooling towers, for example). A few different values will be used to simulate different configurations of the spacing of cooling towers within the power park. For example, the vapor equation reads:

$$\frac{\partial q}{\partial t} = -\vec{V} \cdot \nabla q + \nabla \cdot K \nabla q + \text{SOURCE}$$

where q is the water vapor mixing ratio, $\vec{V}$ is the two-dimensional velocity (u and w components), and K is a nonlinear eddy diffusion coefficient. The SOURCE term will be non-zero at several lower boundary grid points. An appropriate source term value for a 192 km^2 area power park emitting 2.5×10^7 gm sec^{-1} of vapor would be 5.2×10^{-4} gm kg^{-1} sec^{-1} at 50 grid points spaced 200 m apart in the horizontal. This assumes a 10 km by 19.2 km area with the cross section of the model domain taken through the middle of the power park perpendicular to the long axis. This should place the region of integration far enough from the ends of the power park to minimize the edge effects. These effects could only be treated by a full three-dimensional model, which is beyond the capabilities of current computers.

Larger values for the source term at fewer grid points will be used to simulate a closer spacing of the cooling towers. The above value corresponds to a 2.5 mile spacing between tower clusters (four towers to a cluster).

A few cases using different atmospheric conditions will be run to test the effects of the power park on the atmosphere. The results shown above provide a good sample of a severe storm condition and will be rerun with the power park emissions simulated. The two cases will then be compared as to maximum wind speeds, amounts of rain and hail, depth of cloud, cloud base heights, etc., to detect the power park effects. We have conducted similar tests to detect the effects of simulated cloud seeding experiments [36].

Mesoscale convergence effects have been shown to influence significantly convective cloud development in a cloud model [22]. We plan to run the power park cases with values of mesoscale convergence superimposed on the model to see if these effects completely swamp the power park effect.

6. CONCLUDING REMARKS

Power development in the northern Great Plains is taking place in a weather sensitive area -- one characterized by severe thunderstorms, hail, and heavy rains in the summer, and blizzards in the winter. Agriculture is worth billions of dollars to the region's economy and is highly weather dependent -- primarily on rain and hail. Numerical and observational studies of the effects on clouds and storms of waste heat from power plant cooling towers is well within the scientific capabilities of various groups in the area and is now being pursued.

This paper has presented results of a numerical cloud model that gives realistic simulations of severe storms. The modifications to the model to simulate waste heat additions to the atmosphere have been exhibited. The possible effects of "cloud seeding" by the cooling tower plumes in addition to their vapor and heat emissions are being considered.

Acknowledgments. The development of the cloud model has progressed to the present stage because of the programming and scientific expertise of Lansing J. Sloan, Fred J. Kopp, Ray Bryant, and Richard D. Farley.

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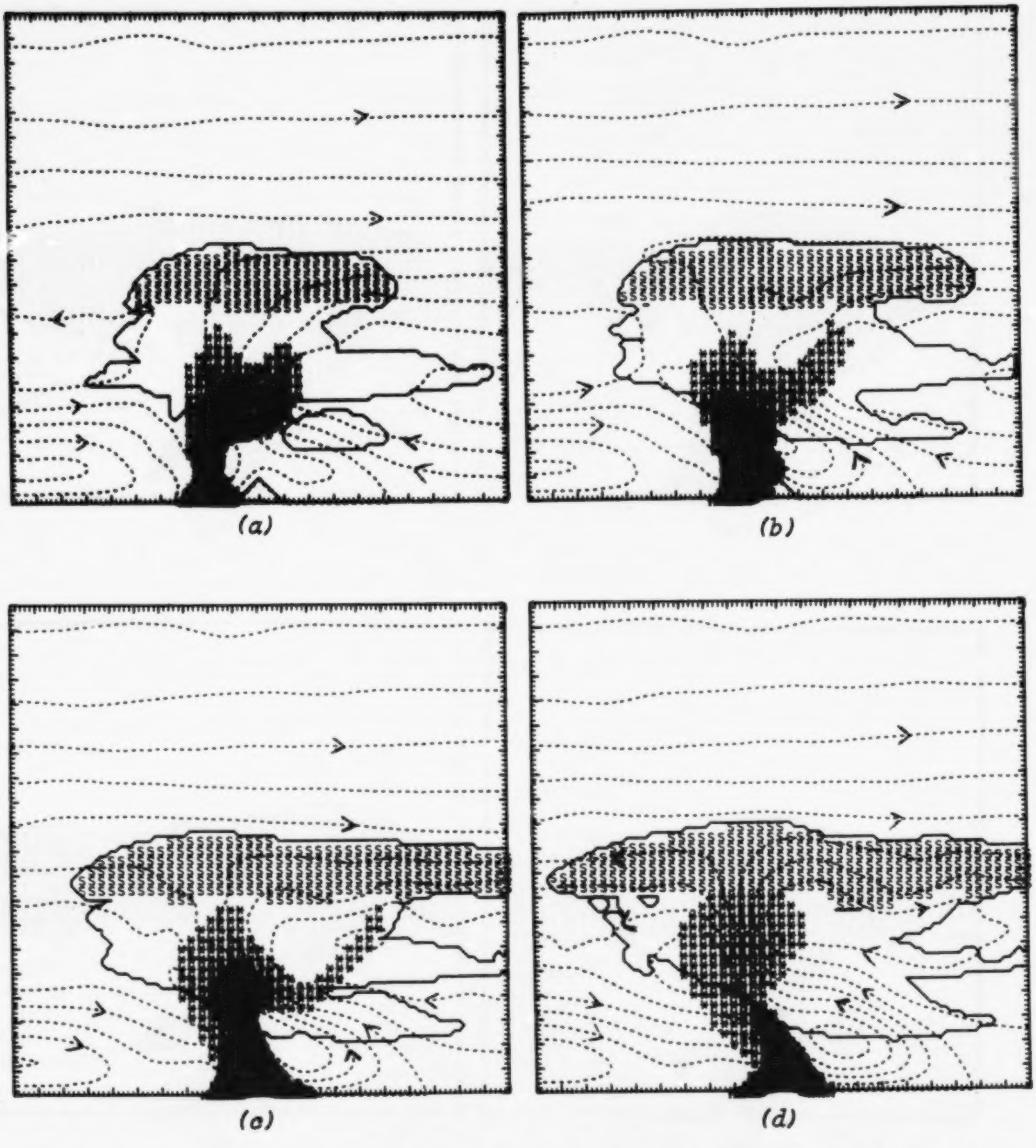
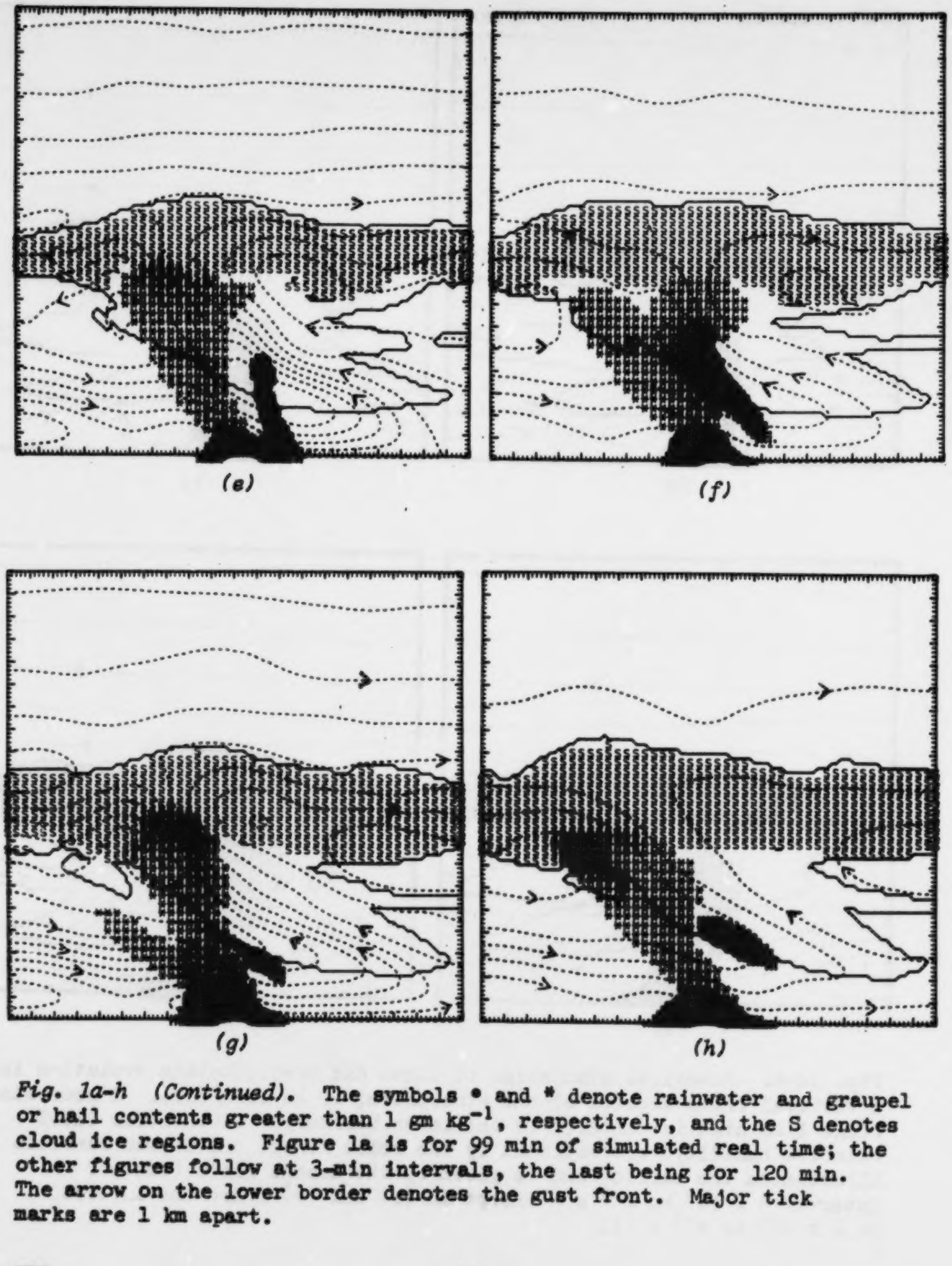


(a) (b) (c) (d)

Fig. 1a-h. Numerical simulation of cloud and precipitation evolution in a vertical cross section of the atmosphere, 20 km on a side. A mountain ridge 1 km high is centered on the lower boundary. Cloud areas (100% relative humidity) are outlined by the solid lines; the stream function illustrates the airflow and is given by the dashed lines (contour interval 5×10^3 kg m^{-1} s^{-1} except in (f) and (h) where the interval is 1×10^4 kg m^{-1} s^{-1}).



(e)

(f)

(g)

(h)

Fig. 1a-h (Continued). The symbols • and * denote rainwater and graupel or hail contents greater than 1 gm kg^{-1}, respectively, and the S denotes cloud ice regions. Figure 1a is for 99 min of simulated real time; the other figures follow at 3-min intervals, the last being for 120 min. The arrow on the lower border denotes the gust front. Major tick marks are 1 km apart.

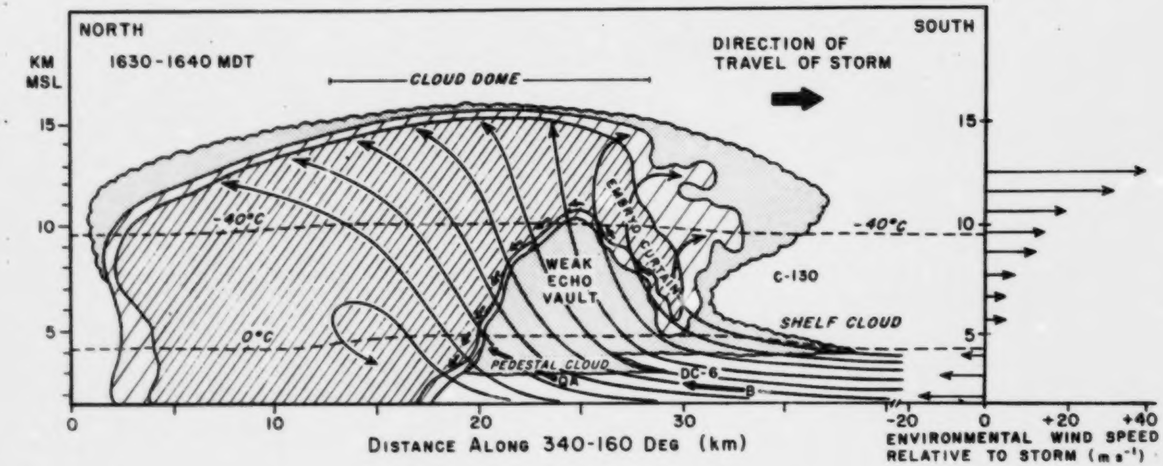

NORTH
SOUTH
1630-1640 MDT
KM MSL
CLOUD DOME
DIRECTION OF TRAVEL OF STORM
-40°C
0°C
WEAK ECHO VAULT
EMBRYO CURTAIN
C-130
SHELF CLOUD
PEDESTAL CLOUD
DC-6
B
DA
15
10
5
0
20
30
-20
+20
+40
DISTANCE ALONG 340-160 DEG (km)
ENVIRONMENTAL WIND SPEED RELATIVE TO STORM (m s⁻¹)

Fig. 2. Vertical section showing features of the visual cloud boundaries of the Fleming storm at 1630-1640 MDT superimposed on the pattern of radar echo. The section is oriented in the direction of travel of the storm. Two levels of radar reflectivity are represented by different densities of hatched shading. Areas of cloud devoid of detectable echo are shown stippled. Short, thin arrows skirting the boundary of the vault represent a hailstone's trajectory. The thin lines are streamlines of airflow relative to the storm drawn to be consistent with the other observations. To the right of the diagram is a profile of the wind component along the storm's direction of travel, derived from a Sterling, Colorado, sounding 50 km south of the storm. (Figure taken from Browning and Foote [35])

omiT

IX-B-83

HEAT PLUMES OVER COOLING RESERVOIRS

by

M. A. Estoque and H. ~~D~~ P. Gerrish

ABSTRACT

The thermal effects in the atmosphere due to heat flux from cooling reservoirs are determined with the aid of a simple model. The governing equation of the model is a highly simplified version of the thermodynamic energy equation. The equation is used to compute the temperature distribution as well as the height of the inversion aloft as a function of the area and temperature of the warm water surface and the prevailing atmospheric temperature distribution. A comparison between the predictions of this simple model with a much more complicated model will be described.

Application of the simplified model to the Florida Power and Light Company reservoir at Turkey Point shows that the height of the heat plume near the downwind edge of the reservoir is about 500 feet during the night and early morning hours. The actual increase in temperature is on the order of a few degrees Fahrenheit at the same location. The consequences of the thermal modification on the dispersion of atmospheric pollutants will be discussed.

SESSION IX-C

CASE STUDIES II

CASE STUDY - FLORIDA POWER AND LIGHT

C. Henderson
Florida Power and Light Company
Miami, Florida

omit

IX-C-89

ASSESSING AND SOLVING ENVIRONMENTAL PROBLEMS OF POWER PLANT COOLING: AN INTEGRATED APPROACH

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We are developing quantitative methods to determine the impact of flow-through power plant cooling on aquatic environments, and methods to reduce the impact to acceptable levels while maintaining the highest possible power-plant operating efficiency at lowest possible cost. This work integrates three elements:

(1) remote sensing of temperature and other water quality parameters, and terrestrial vegetative effects, using advanced aerial survey techniques;

(2) formulation of a quantitative approach to assessing thermal impact in a biologically meaningful way;

(3) development of experimental devices to evaluate in-plant thermal and chemical effects on entrained organisms, and to reduce the percentage of organisms entrained and organisms impinging on intake screens.

The remote sensing work covers precise measurement of thermal and chemical impacts of cooling water discharged from power plants. Water temperature discharge data for forty-three power plants and sites in New York State were measured by a new aerial infrared method that does not require ground truth. Work nearing completion is aimed at validating the new method as traceable to the National Bureau of Standards, in order to make the results acceptable under measurement requirements of state and federal governments.

Another part of the work combines mathematical models of thermal effects in rivers and lakes with data obtained from the aerial infrared temperature measurements, in order to determine the temperature distribution throughout the volume of a water body, at depths significant for environmental effects. The results of this work will enable reduction of expensive water temperature surveys made from boats.

We are studying entrainment of organisms with a condenser simulator, a diagnostic system we developed to measure entrainment effects under controlled conditions.

We have developed a design concept for a new type of condenser intake structure that would greatly reduce fish kills by impingement. A design study is now being conducted, looking toward experimental development.

A quantitative formulation of thermal impact on aquatic organisms is being developed that will apply the results of our experimental programs to obtain a quantitative evaluation of impact and a method of formulating power-plant cooling system design criteria to reduce the impact to acceptable levels.

The approaches being followed and results to date are described.

14-45-22

IX-C-91

THERMAL PLUME EVALUATION PROGRAM OF INDIAN POINT NUCLEAR POWER PLANT

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ABSTRACT

A thermal plume study has been formulated by Con Edison to demonstrate that plant thermal discharges from the Indian Point Unit No. 2 station to the Hudson River will satisfy all applicable water quality criteria. This program consists of physical modelling, mathematical analysis and field surveys. Two distinct physical models were used: a 1/75 scale, undistorted model for obtaining detailed temperature patterns in the vicinity of the discharge structure, and an overall distorted scale model for obtaining far field temperature patterns. A one-dimensional, tidal average hydrothermal mathematical model in which the Hudson River is separated into 28 longitudinal segments was developed; therefore, space-variable parameters, such as river geometry, dispersion coefficient and thermal stratification, can be introduced for computation. The field surveys provided field data for assessing the predictive capabilities of the physical and mathematical model. Model-prototype comparisons indicate that both the physical and analytical models tend to be conservative; that is, predict greater than measured extents for the thermal plume.

INTRODUCTION

Indian Point Unit No. 2 is a 906 MWe (turbine net rating) pressurized water reactor power plant located on the east shore of the Hudson River estuary, about 43 miles north of the Battery, near the Village of Buchanan, New York. (The station consists of three units, Indian Point Unit Nos. 1, 2 and 3). The condenser heat load, which is about 6.25 billion Btu/hr., is rejected to a once-through cooling system with a submerged multiport discharge structure (Figure 1).

The New York State thermal discharge criteria applicable to the Hudson River estuary are as follows:

> The water temperature at the surface of an estuary shall not be raised to more than 90°F at any point provided further, at least 50 percent of the cross sectional area and/or volume of the flow of the estuary including a minimum of one third of the surface as measured from water edge to water edge at any stage of tide, shall not be raised to more than 4°F over the temperature that existed before the addition of heat of artificial origin or to a maximum of 83°F, whichever is less. However, during July through September if the water temperature at the surface of an estuary before the addition of heat or artificial origin is more than 83°F, an increase in temperature not to exceed 1.5°F, at any point of the estuarine passageway as delineated above, may be permitted.

Prior to full power operation of Indian Point Unit No. 2 in 1973, both physical and analytical models were developed as predictive tools for describing the hydrothermal response of the Hudson River to the thermal effluent of Unit No. 2 and other neighboring power plants. The results of the model studies have been incorporated into the Indian Pint 2 Environmental Report and its supplements which have been reviewed by various governmental agencies, incuding the United States Nuclear Regulatory Commission (NRC), United States Environental Protection Agency, and the New York State Department of Enviromental Conservaton (DEC). In 1973, Con Edison received from NRC a facility operating license and from EPA a discharge permit (pursuant to Section 402 of the FWPCA) for Indian Point Unit No. 2. The provisions contained in these regulatory documents required Con Edison conduct a thermal monitoring program to evaluate the thermal effluent from Indian Point Unit No. 2 for purposes of comparision with both the thermal dishcarge criteria and the predictions from the physical and mathematical models.

This paper discusses the technical aspects of the physical and mathematical models, field study and model-prototype comparision.

PHYSICAL MODEL

A physical model is a small scale physical structure simulating the geometry and hydrology of both the thermal effluent and the receiving water body. The basic dynamic and kinematic similitude of physical modeling is based on the relative magnitude of inertial to gravity forces, which is represented by the Froude number for flow with a constant density fluid, and by the densimetric Froude number for stratified flow. The Froude numbers should be equal between model and prototype for both free surface and internal density phenomena occur simultaneously.

Two distinct physical models were developed by Alden Research Laboratories (ARL):

1. Near field hydrothermal characteristics of the thermal effluent were investigated using an undistorted 1/75 scale model which simulated an area 4000 feet long by 2000 feet wide centered about the dishcarge. Currents ranging 0.5 to 2.0 feet per second can be simulated in both ebb and flood directions.

2. Far field thermal plume phenomena were investigated by a distorted scale model, 1/80 vertical and 1/400 horizontal, covering 17 miles of the river as shown in Figure 2. In this model, near field jet mixing phenomena were adjusted by modification of the outfall configuration to duplicate temperature patterns obtained from the undistorted scale model.

The physical models are located inside a building for control of atmospheric conditions to assure constant ambient temperature. However, water-atmosphere interface heat exchange could not be independently controlled. Since fresh water was employed in all tests, salinity variations could not be simulated. Temperature measurements were made with thermocouple sensors, and digital computer controlled data sampling and data processing. Temperature patterns were recorded at one-hour (prototype time scale) intervals for several complete tidal cycles.

MATHEMATICAL MODEL

The Hudson is an estuary which might probably be best described by a multi-dimensional transient mathematical model. However, seeking a numerical solution to such a set of differential equations governing the mass and energy transport phenomena of estuarine thermal dispersion is difficult.

A simple, practical analytical model was developed for the Indian Point study. This is a multi-segment one-dimensional steady-state model capable of accepting multiple thermal discharges. The river is mathematically separated into 28 segments; therefore, space-variable parameters, such as river geometry, dispersion coefficient and thermal stratification, can be realistically introduced for computation.

The differental equation resulting from the energy balance on a river element is as follows:

$$E_i \cdot \frac{d^2\Delta\bar{T}_i}{dx^2} - \frac{Q_i}{A_i}\cdot\frac{d\Delta\bar{T}_i}{dx} - \frac{\bar{k}_i B_i (TSF)_i}{\rho C_p A_i}\cdot\Delta\bar{T}_i = 0$$

where

$\Delta\bar{T}$ = tidal-smoothed, area-averaged temperature rise, $^\circ F$

E = longitudinal dispersion coefficient, Ft^2/day
Q = river freshwater flow, $feet^3$/day
A = cross-sectional area of the estuary, $feet^2$
$\bar{k}$ = heat transfer coefficient, BTU/$feet^2$/day/$^\circ F$
B = top width of the estuary, feet
TSF = thermal stratification factor, $\Delta\bar{T}s/\Delta\bar{T}$
$\Delta\bar{T}_s$ = surface average temperature rise, $^\circ F$
ρ = water density, lb/$feet^3$
C_p = heat capacity, BTU/lb/$^\circ F$
i = segment subscript; $i = 1,2,3,\ldots\ldots,n$ and $n=28$
L = segment length, feet
x = distance along river

The general solution of the ordinary differential equation above is:

$$\Delta\bar{T}_i = C_i \exp(J_i x) + D_i \exp(k_i x)$$

in which

$$\begin{matrix}J_i\\ k_i\end{matrix} = \frac{Q_i}{2A_iE_i}\left\{1 \pm \left[1+\frac{4\bar{k}_iB_i(TSF)_iE_iA_i}{\rho C_p Q_i^2}\right]^{\frac{1}{2}}\right\}$$

The integration constants, Ci and Di can then be determined by the boundary conditions.

B.C. 1: $\Delta\bar{T}(\chi=0) = 0$

B.C. 2: $\Delta\bar{T}\left(\chi=\sum_{i=1}^{n} x_i\right)=0$

B.C. 3: $\Delta\bar{T}_i\left(\chi=\sum_{i=1}^{i} x_i\right) = \Delta\bar{T}_{i+1}\left(\chi=\sum_{i=1}^{i} x_i\right) \quad ; \; i = 1,2,\cdots,(n-1)$

B.C. 4: $H_i = \rho C_p \left\{ E_i A_i \frac{d\Delta\bar{T}_i}{d\chi} - E_{i+1} A_{i+1} \frac{d\Delta\bar{T}_{i+1}}{d\chi} \right\}_{\chi=\sum_{i=1}^{i} x_i} ; \; i = 1,2,\cdots(n-1)$

The first two boundary conditions represent zero excess temperature at the upper and lower ends of the Hudson River. Boundary Conditons 3 and 4 state equality of temperature and a conservation of eneqy (Hi) at intermediate sections, respectively.

Once the tidal-averaqed, area averaqed temperturo rise $(\Delta\bar{T})$ is calculated, the surface average temperature rise $(\Delta\bar{T}_s)$ can then be computed by

$$(\Delta\bar{T}_s)_i = (\Delta\bar{T})_i \cdot (TSF)_i$$

Two empirical equations were developed to predict the cross-sectional areas (α_χ) and surface width (β_χ) of the river bounded by an isotherm representing a specific temperature rise (ΔT_χ).

$$\alpha_\chi = \frac{1}{\hat{K}_1} \cdot \ln\left(\frac{\Delta\hat{T}_A}{\Delta T_\chi}\right)$$

$$\beta_\chi = \frac{1}{\hat{K}_2} \cdot \ln\left(\frac{\Delta\hat{T}_s}{\Delta T_\chi}\right)$$

where the decay parameters $\hat{K}1$ and $\hat{K}2$ can be evaluated by the equations:

$$\frac{\Delta T}{\Delta\hat{T}_A} = \left[\frac{1}{\hat{K}_1 A}\right]^{(1-\exp\{-\hat{K}_1 A\})}$$

$$\frac{\Delta T_s}{\Delta\hat{T}_s} = \left[\frac{1}{\hat{K}_2 B}\right]^{(1-\exp\{-\hat{K}_2 B\})}$$

and A and B are the river cross-sectional area and surface width, and $\Delta\hat{T}_A$ and $\Delta\hat{T}_s$ are the maximum cross-sectional area and maximum surface temperature rises at a specific cross plane of the river.

FIELD PROGRAM

The field program was geared to satisfy two complementary objectives. (1) provide data in describing the spatial and temporal characteristics of the thermal plume, and (2) provide data for estimating the physical parameters used in the aforementioned hydrothermal models to enable a model-prototype comparison.

The Indian Point Unit No. 2 field survey program, which was conducted from May 1974 to may 1975, consisted of nine thermal surveys: six routine and three intensive surveys.

A routine thermal survey consists of measurements of the intensity and extent of the Indian Point plume over five successive tidal phases - that is 1 1/4 tidal cycles (i.e., maximum ebb, low water slack, maximum flood, high water slack and maximum ebb again). Data from a routine survey was sufficient to describe the general pattern of the thermal plume and thus could be used for comparison with the thermal critiera.

An intensive thermal survey consists of similar measurements conducted over four or five scccessive tidal phases for three or four days. Also more detailed measurements (than in a routine survey) of ancillary hydrological and meteorological parameters are acquired. Therefore, data from an intensive survey are utilized for model analysis.

Summary data from the Indian Point Unit No. 2 thermal survey program are shown in Table 1.

The methodology used to acquire thermal plume temperature information was common to both routine and intensive surveys, and is based upon the fact that plume behavior varies with distance from the discharge. A thermal plume is usually divided into near field, intermediate field, and far field regions. The near field is the region in the immediate vicinity of the discharge, where the initial momentum of the effluent jet governs the temperature distribution of the plume. The far field is the region wherein the effect of jet momentum is negligible; and the resultant temperature patterns are determined by the ambient currents of the receiving waterbody and atmospheric heat transfer. In the intermediate field, both the momentum of the effluent jet and ambient waterbody currents influence the plume pattern. Figure 3 depicts these regions.

Recalling that Indian Point has a submerged multiport discharge structure, the actual plume measurements can therefore be divided into those conducted in the near and intermediate field, and those obtained in the far field; because the plume in the near and intermediate field extends to a greater depth than in the far fiell. During the surveys, at least two boats were used, one for the near and intermediate region and the other for the far field. Near field measurements were obtained via a string of thermistors extending to a depth of about 20 feet, attached to a vessel making a criss-cross pattern over the near and intermediate field. The far field was mapped through the use of thermistors concentrated near the surface (up to a depth of six feet), with the vessel making many transects across the river. Vessel speed ranged from 2 to 8 knots, with the temperature being continuously recorded. This pattern was repeated over each phase of the tidal cycle. An electronic navigation system (a Motorola Mini-Ranger) on each vessel gave the location of each temperature measurement with respect to the shore based transponders. The temperatures, location and time of each measurement was recorded either on magnetic tape of by a printer as the boat scans the plume. Figure 4 depicts the scanning arrangements.

The plume measurements from the near and far field patterns were both combined to present the total temperature pattern. Figures 5 to 9 illustrate typical ebb and flood patterns. The decrease in temporal with depths as well as the buoyant behavior of the plume can be noted from comparison the surface flood pattern (Figure 5) with the 3-foot depth (Figure 6) and 14-foot depth flood patterns (Figure 7). The surface and 3-foot ebb patterns are shown in Figures 8 and 9 respectively. Station output during this survey was approximately 270 MWe (net) and 770 MWE (net) for Unit Nos. 1 and 2, respectively.

The acquisition of the hydrogical and meteorological data necessary for comparison with the models can best be described by reference to the specific parameters:

(a) fresh water flow: the fresh water flow past Indian Point is obtained by multiplying the recorded fresh water flow at the upstream head of the Hudson (at Troy Dam) by a factor obtained from historical records;

(b) meteorological data: The meteorological data, including air temperature, relative humidity, wind speed and solar radiation is obtained from a meteorological station located at the site. This data is necessary to evalute the heat transfer coefficient for model analysis;

(c) longitudinal dispersion coefficient: this parameter is estimated from the measured salinity distribution in the river;

(d) thermal stratification factor: this parameter is evaluated from the three dimensional isotherm patterns constructed from the plume temperature data.

MODEL-PROTOTYPE COMPARSION

The physical and mathematical models described previously were tested for conditions similar to the prototype on the 20 through 24 August, 1974, and 22 through 24 October, 1974. Input parameters for model testing include plant heat load, fresh water flow, surface heat exchange, thermal stratification factors and longitudinal dispersion coefficients. To avoid repetition, model-prototype comparision for the August 1974 thermal survey is selected for presentation.

Analyses on Physical Modeling

A total of three tests series were conducted using the physical models:

August, 1974 Survey Simulation

Test Series No.	Fresh Water Flow, cfs		Heat Transfer Coeff. Btu/ft.^{2}-day-°F	
	Model	Prototype	Model	Prototype
2	6,400	6,400	149	178-200
7	35,000	6,400	145	178-200
13	20,800	6,400	149	178-200

Isotherms representing flood and ebb conditions are shown in Figures 10 and 11.

A comprehensive analysis reveals that, in general, the surface isotherm pattern predicted by the model bears a remarkable similarity to the prototype result; however, the former is found to be highly conservative when recorded freshwater runoff values were directly simulated (i.e., the model prediction for a specific isotherm pattern is exaggerated). As illustrated in Figure 12 the overall surface isotherm patterns from both the model and the prototype are similar, yet by comparing individual isotherms of identical strength (temperature rise), the field conditions have been over-estimated by the model.

The conservatism of the model is primarily due to the lack of similitude in physical modelling. The most severe limitation of the existing model is its incapability in simulating in an estuary the natural phenomena of net non-tidal flow as a result of salinity intrusion due to upstream moving seawater coupled with a counter current flow of fresh water.

This two layer counterflow would result in a vertical mixing, and, thus, the effective water available for thermal dilution is much higher than the freshwater runoff. The physical model is not equipped to simulate such a two-layer flow. In an attempt to account for the added dilution due to the two-layer flow, the freshwater flow rate used in the model tests was increased in accordance with the hydrological analysis for the Hudson River. Figures 13A and 13B presented the physical model surface isotherm pattern for flood for the August survey with freshwater flow of 20,800 cfs and 35,000 cfs, respectively. By comparing Figure 13 to Figure 12 it is observed that the magnitude of the surface isotherms were underestimated by a freshwater flow rate higher than 20,800 cfs. A freshwater flow between 6,400 cfs and 20,800 cfs could probably be the best value in order to duplicate flood data of the August survey. However, the optimum freshwater flow for duplicating the ebb data of the August survey was between 20,800 cfs and 35,000 cfs.

The second "lack of similitude" of the ARL's distorted scale model involves the modelling of the outfall structure of the Lovett power plant. Because of insufficient field data, the Lovett outfall has not been satisfactorily calibrated. Basically, the lateral spread of the Lovett thermal plume employed in the model was larger than indicated by the field data. As a result of this modelling shortcoming, the thermal impact attributable to the operation of the Lovett power plant has been grossly exaggerated as shown in Figure 14. It is noticed that by incrasing the model freshwater flow from 6,400 cfs, which is the estimated freshwater flow, to 35,000 cfs, the 4°F temperature rise isotherm attributable to the operation of Indian Point power plant was forced to duplicate the prototype data. The thermal plume emanating from the Lovett discharge appeared to be insensitive to the adjustment of freshwater flow. Nevertheless, the exaggeration of the Lovett thermal plume, laterally and longitudinally, is obvious by comparing Figure 14A to Figures 14B and 14C.

Other modelling limitations which cannot be ignored include:

(1) the inability to simulate the surface heat exchange rate,

(2) the difficulty of duplicating the tide state and velocities, and

(3) the loss of heat due to warm water transfer through the downstream boundaries.

Analysis on Mathematical Model

Figure 15 presents the comparisin between the analytical model prediction and the field data, using August 20, 1974 conditon. Included in the simulation are the heat discharge from two downstream facilities, Lovett and Bowline Generating Stations. As can be seen, the model prediction is conservative, for it overestimates the intensity of the thermal plume. This conservative behavior is probably due to the difficulty in using a steady state, analytical model to predict the transient behavior of a thermal plume. In addition, the steady state model cannot describe the intra-tidal variation in hydrological and meteorological conditions, and the unsteady operation conditions of the power plants. Nevertheless, the model can predict, conservatively, the intensity and extent of a given perturbation on the estuary, for example, what effect a reduction in fresh water flow will have on the intensity and extent of the thermal effluent.

CONCLUSION

Three methods; physical modelling, analytical modelling and field measurements have been utilized to quantify the intensity of the thermal plume from Indian Point Unit No. 2.

In general, the Indian Point Unit No. 2 thermal plume evaluation program has achieved its primary objectives. It provided data necessary for preparing various environmental statements and other official documents (including input to biological studies), and satisified various licensing conditions imposed by government agencies.

GENERAL REFERENCES

1. Consolidated Edison Company of New York, Indian Point Unit No. 2 Environmental Report, Appendix K: Effect of Indian Point Cooling Water Discharge on Hudson River Temperature Distribution, prepared by Lawler, Matusky & Skelly Engineers, February, 1969.

2. Indian Point Nuclear Generating Station Intensive Thermal Survey Program, August and October, 1974, prepared by Dames & Moore and Consolidated Edison Company of New York, March 1976.

TABLE I

INDIAN POINT THERMAL SURVEY SUMMARY

SURVEY (1) (DATE)	MWe (2)	MAX. TIDAL PHASE (3)		
		EXCESS TEMP. °F	% RIVER WIDTH (4) (TIDAL PHASE)	% CROSS-SECTIONAL (5) AREA (TIDAL PHASE)
1.(5/31/74)	1075	3.2	46 (LWS)	19 (LWS)
2.(6/13/74)	975	3.9	36 (LWS)	16 (LWS)
3.(7/17/74)	810	3.8	40 (EBB)	15 (FLOOD)
4.(8/20-24/74)	1140	3.8	33 (HWS)	14 (HWS)
5.(9/24/74)	1135	4.0	35 (LWS)	20 (LWS)
6.(10/22-25/74)	1160	3.9	53 (LWS)	18 (LWS)
7.(11/20/74)	700	4.0	49 (LWS)	18 (LWS)
8.(4/23/75)	900	4.0	18 (HWS)	6 (FLOOD)
9.(5/13-15/75)	900	4.0	16 (LWS)	5 (LWS)

Notes: (1) Routine Survey: Series 1,2,3,5,7 & 8. Intensive Survey: Series 4,6 & 9

(2) Total MWe from Units 1 and 2. IP1 not operating since 11/74.

(3) "Max. Tidal Phase" is designated as the tidal phase at which the most severe thermal impacts occurred.

(4) Percent of the river surface width bounded by the isotherm representing the excess temperature.

(5) Present of the river cross-sectional area bounded by the isotherm representing the excess temperature.

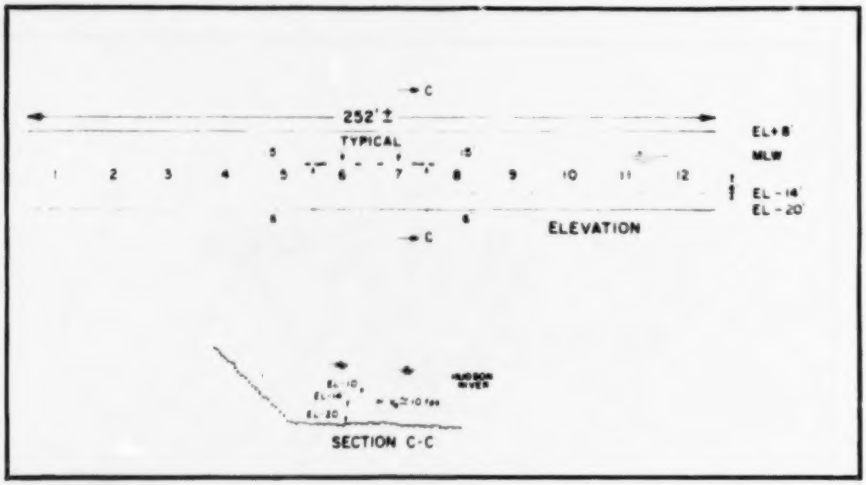

C
252' ±
EL+8'
TYPICAL
MLW
1
2
3
4
5
6
7
8
9
10
11
12
EL -14'
EL -20'
ELEVATION
C
EL -10
EL -14
EL -20
HUDSON RIVER
SECTION C-C

Figure 1. Details of Discharge Structure

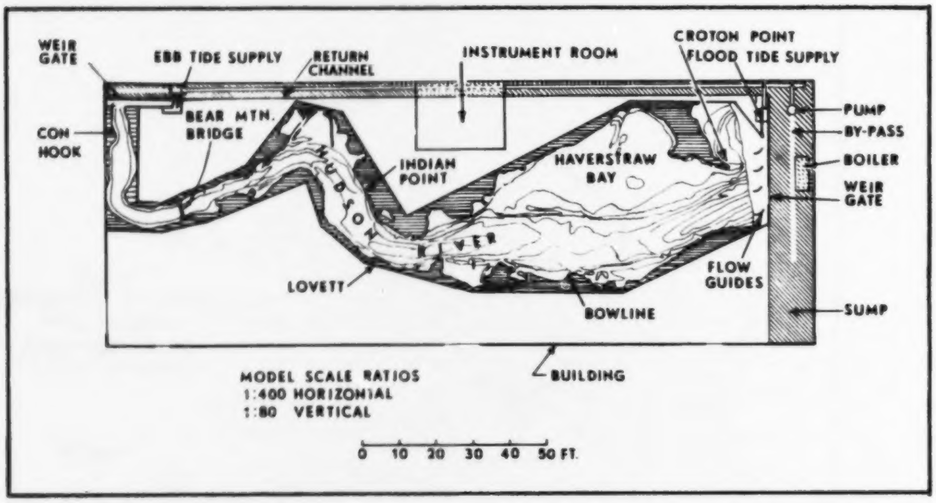

WEIR GATE
EBB TIDE SUPPLY
RETURN CHANNEL
INSTRUMENT ROOM
CROTON POINT
FLOOD TIDE SUPPLY
PUMP
BY-PASS
BOILER
WEIR GATE
CON HOOK
BEAR MTN. BRIDGE
HUDSON RIVER
INDIAN POINT
HAVERSTRAW BAY
LOVETT
FLOW GUIDES
BOWLINE
SUMP
BUILDING
MODEL SCALE RATIOS
1:400 HORIZONTAL
1:80 VERTICAL
0
10
20
30
40
50 FT.

Figure 2. Distorted Physical Model

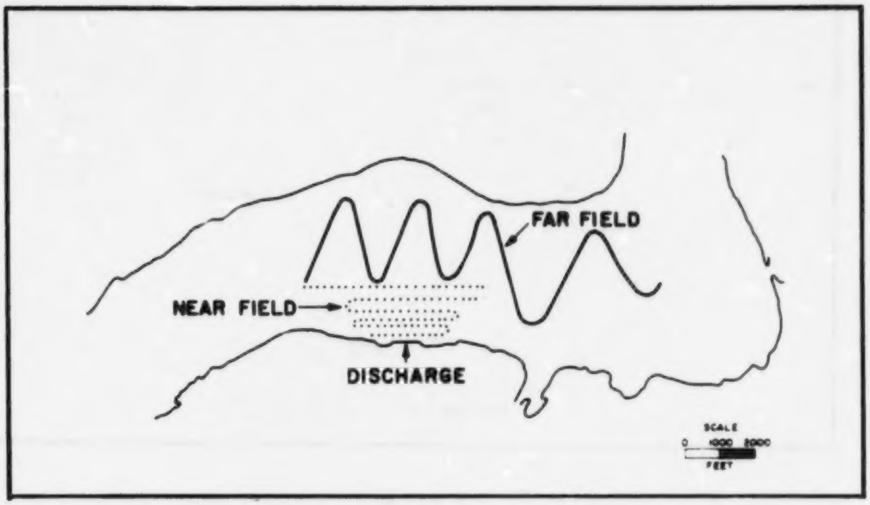

FAR FIELD
NEAR FIELD
DISCHARGE
SCALE
0 1000 2000
FEET

Figure 3. Typical Near & Far Field Scans

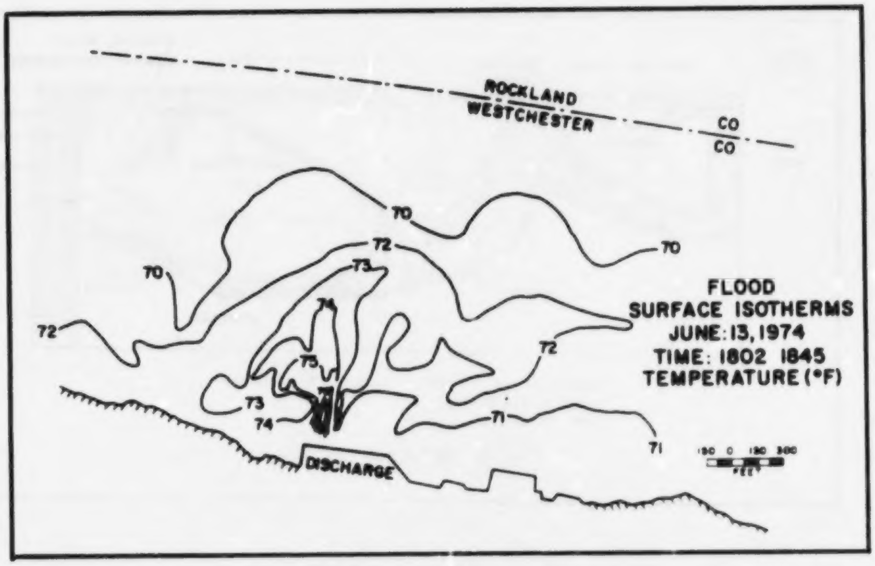

ROCKLAND CO
WESTCHESTER CO
70
72
73
74
75
71
FLOOD
SURFACE ISOTHERMS
JUNE: 13, 1974
TIME: 1802 1845
TEMPERATURE (°F)
DISCHARGE
150 0 150 300
FEET

Figure 5. Flood Surface Isotherms

351< Hcm

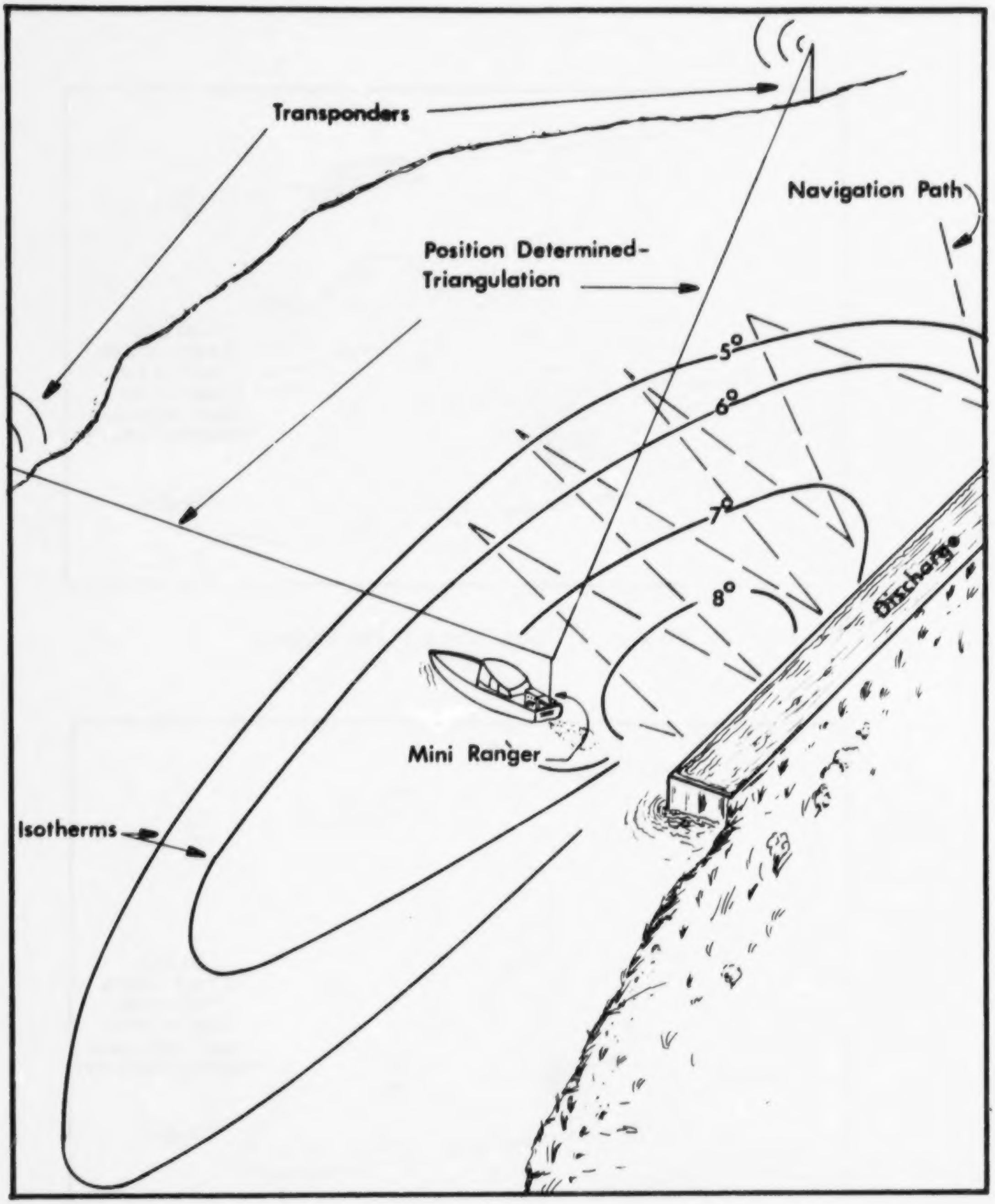

Transponders
Navigation Path
Position Determined-
Triangulation
5°
6°
7°
8°
Discharge
Mini Ranger
Isotherms

Figure 4. Schematic of Thermal Scanning

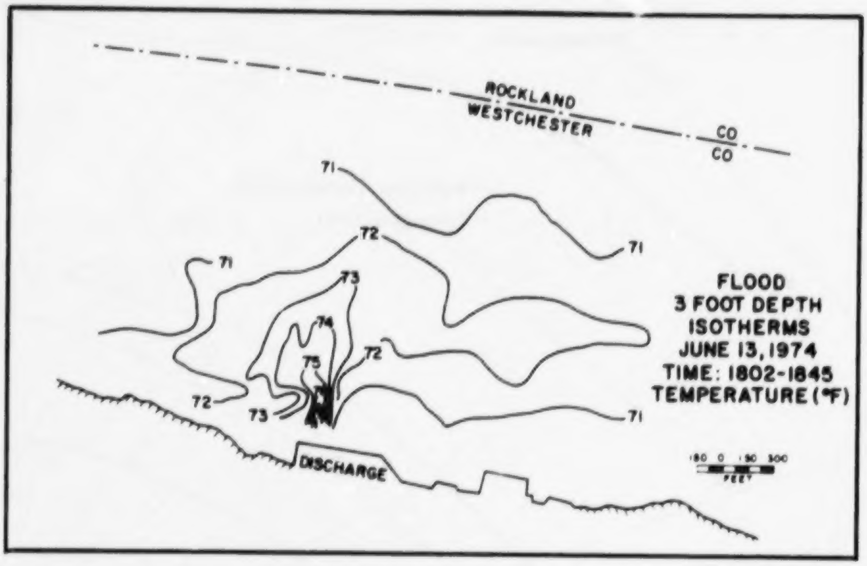

ROCKLAND
WESTCHESTER
CO
CO
71
72
71
73
74
75
72
71
72
73
71
FLOOD
3 FOOT DEPTH
ISOTHERMS
JUNE 13, 1974
TIME: 1802-1845
TEMPERATURE (°F)
DISCHARGE
150 0 150 300
FEET

Figure 6. Flood 3-Foot Depth Isotherms

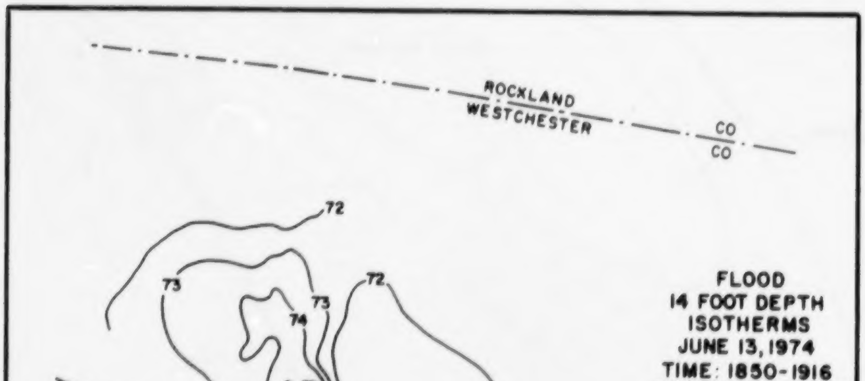

ROCKLAND
WESTCHESTER
CO
CO
72
73
72
73
74
75
72
FLOOD
14 FOOT DEPTH
ISOTHERMS
JUNE 13, 1974
TIME: 1850-1916
TEMPERATURE (°F)
DISCHARGE
150 0 150 300
FEET

Figure 7. Flood 14-Foot Depth Isotherms

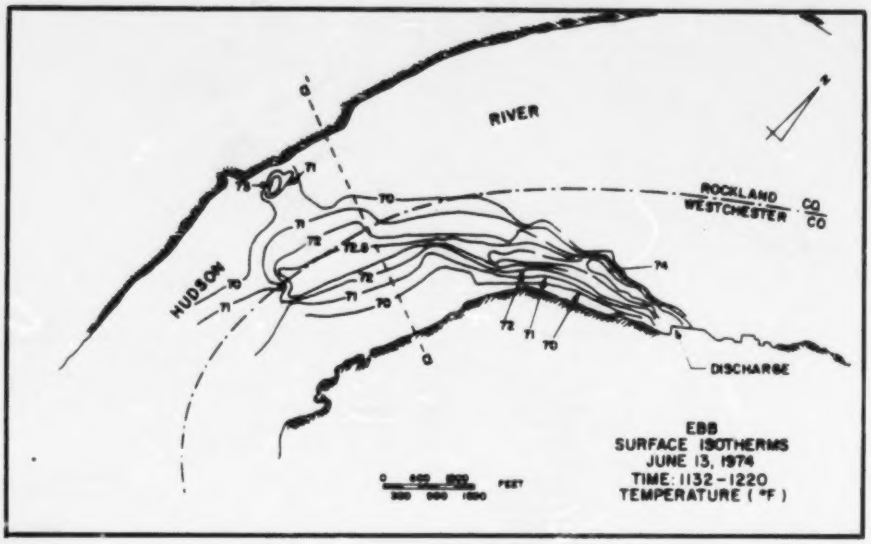

RIVER
HUDSON
ROCKLAND CO
WESTCHESTER CO
O'
O
71
73
70
71
72
72.5
72
71
70
70
71
74
72
71
70
DISCHARGE
N
0 600 1200 FEET
300 900 1800
EBB
SURFACE ISOTHERMS
JUNE 13, 1974
TIME: 1132-1220
TEMPERATURE (°F)

Figure 8. Ebb Surface Isotherms

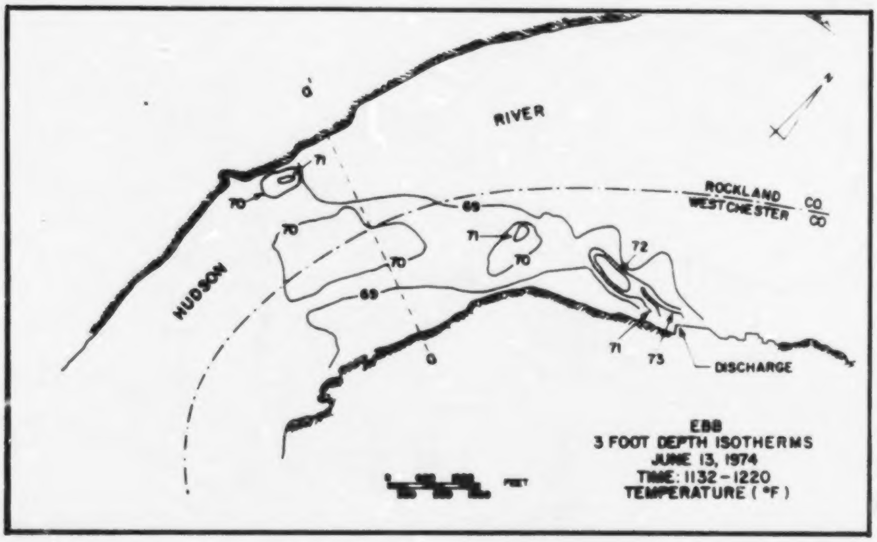

RIVER
HUDSON
ROCKLAND CO
WESTCHESTER CO
O'
O
71
70
69
70
71
70
70
72
69
71
73
DISCHARGE
N
FEET
EBB
3 FOOT DEPTH ISOTHERMS
JUNE 13, 1974
TIME: 1132-1220
TEMPERATURE (°F)

Figure 9. Ebb 3-Foot Depth Isotherms

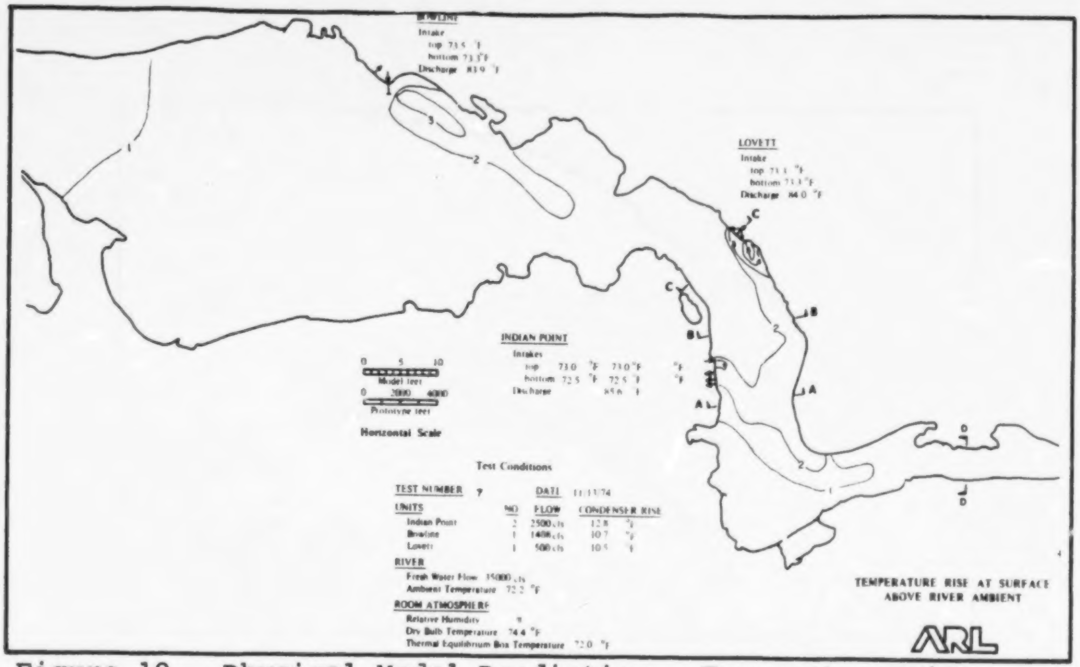

BOWLINE
Intake
top 73.5 °F
bottom 73.3 °F
Discharge 83.9 °F
3
2
1
LOVETT
Intake
top 73.3 °F
bottom 73.3 °F
Discharge 84.0 °F
C
C
B
B
A
A
D
D
2
2
1
INDIAN POINT
Intakes
top 73.0 °F 73.0 °F °F
bottom 72.5 °F 72.5 °F °F
Discharge 85.6 °F
0 5 10
Model feet
0 2000 4000
Prototype feet
Horizontal Scale
Test Conditions
TEST NUMBER 7
DATE 11/13/74
UNITS NO FLOW CONDENSER RISE
Indian Point 2 2500 cfs 12.8 °F
Bowline 1 1400 cfs 10.7 °F
Lovett 1 500 cfs 10.5 °F
RIVER
Fresh Water Flow 35000 cfs
Ambient Temperature 72.2 °F
ROOM ATMOSPHERE
Relative Humidity %
Dry Bulb Temperature 74.4 °F
Thermal Equilibrium Box Temperature 72.0 °F
TEMPERATURE RISE AT SURFACE ABOVE RIVER AMBIENT
ARL

Figure 10. Physical Model Prediction - Temperature Rise at Surface of Flood for August, 1974 Survey

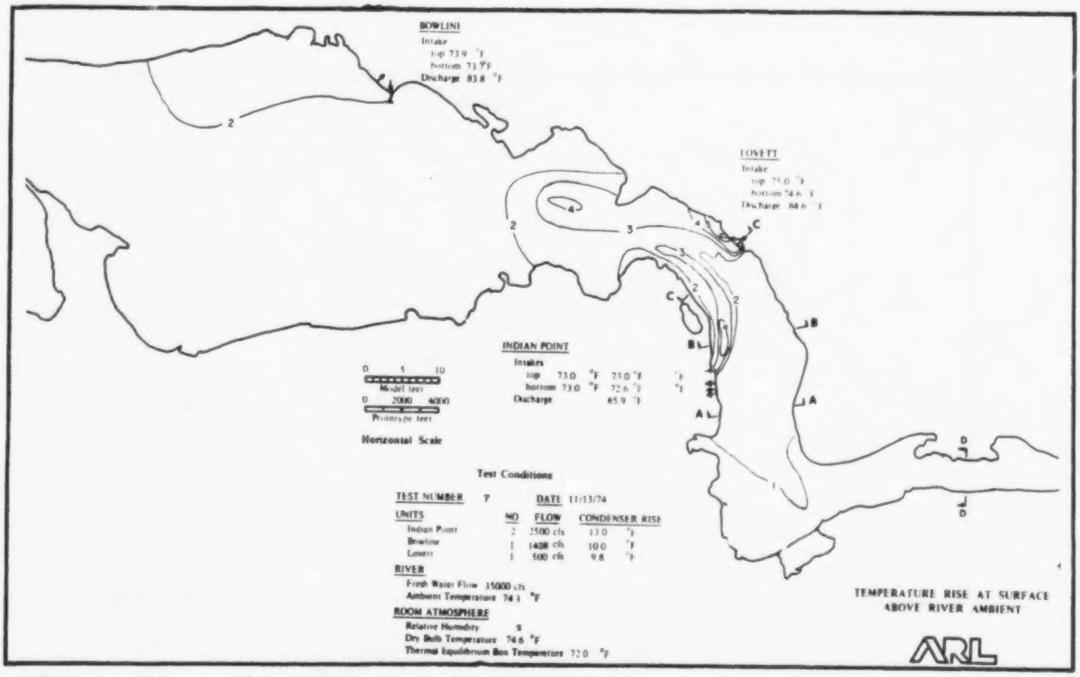
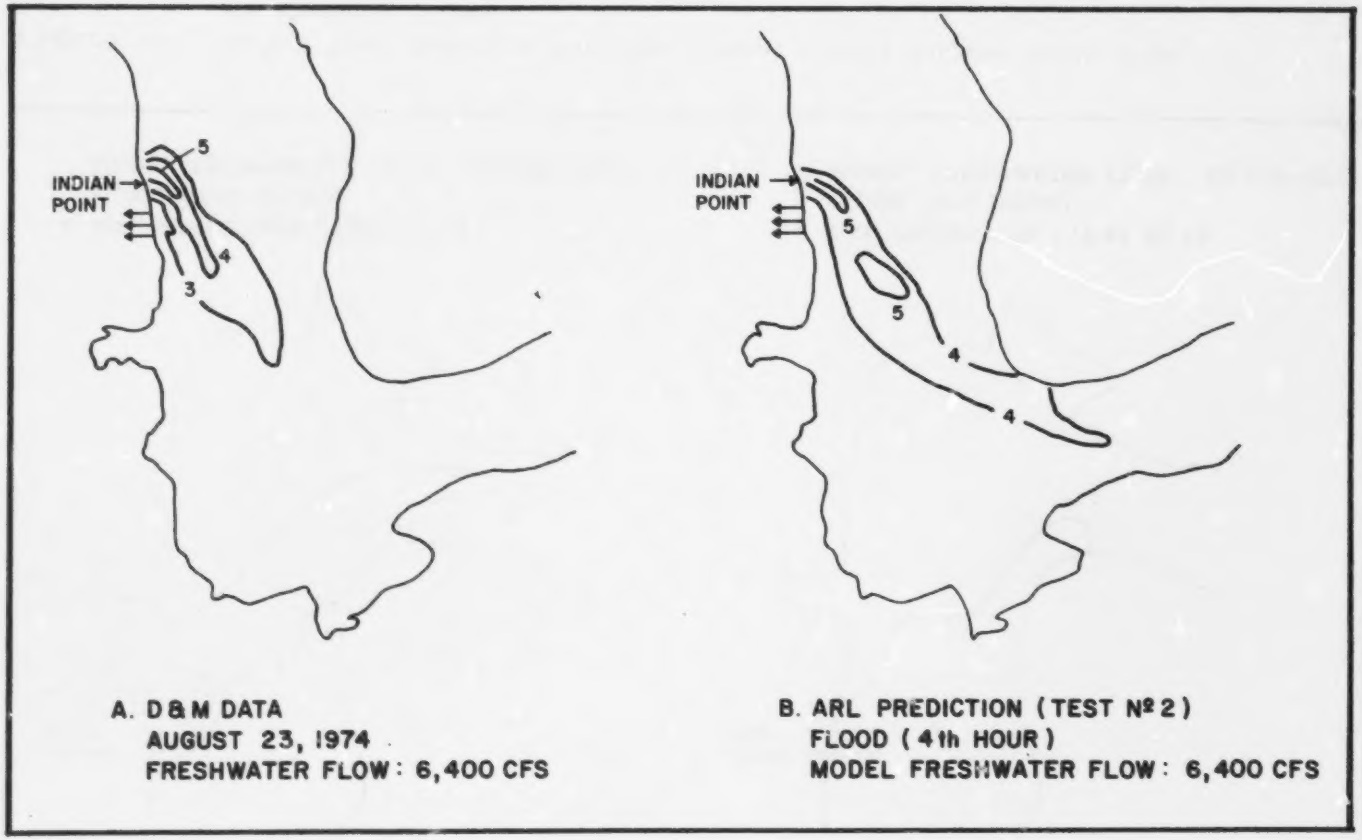

BOWLINE
Intake
top 73.9 °F
bottom 73.7 °F
Discharge 83.8 °F
2
LOVETT
Intake
top 75.0 °F
bottom 74.6 °F
Discharge 84.6 °F
4
3
2
4
3
2
2
C
C
B
B
A
A
D
D
1
INDIAN POINT
Intakes
top 73.0 °F 73.0 °F °F
bottom 73.0 °F 72.6 °F °F
Discharge 85.9 °F
0 5 10
Model feet
0 2000 4000
Prototype feet
Horizontal Scale
Test Conditions
TEST NUMBER 7
DATE 11/13/74
UNITS NO FLOW CONDENSER RISE
Indian Point 2 2500 cfs 13.0 °F
Bowline 1 1400 cfs 10.0 °F
Lovett 1 500 cfs 9.8 °F
RIVER
Fresh Water Flow 35000 cfs
Ambient Temperature 74.1 °F
ROOM ATMOSPHERE
Relative Humidity %
Dry Bulb Temperature 74.6 °F
Thermal Equilibrium Box Temperature 72.0 °F
TEMPERATURE RISE AT SURFACE ABOVE RIVER AMBIENT
ARL

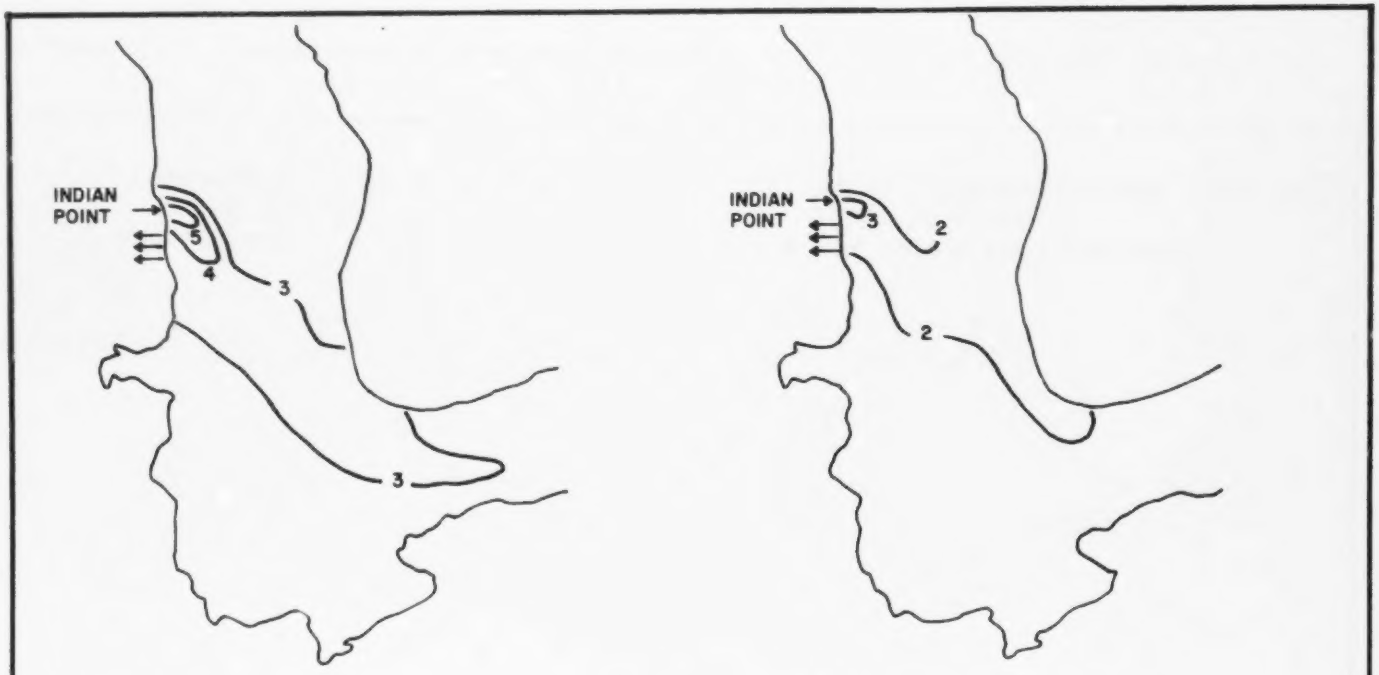
Figure 11. Physical Model Prediction - Temperature Rise at Surface of Ebb for August, 1974 Survey


5
INDIAN POINT
4
3
INDIAN POINT
5
5
4
4

A. D&M DATA
AUGUST 23, 1974
FRESHWATER FLOW: 6,400 CFS

B. ARL PREDICTION (TEST Nº 2)
FLOOD (4th HOUR)
MODEL FRESHWATER FLOW: 6,400 CFS

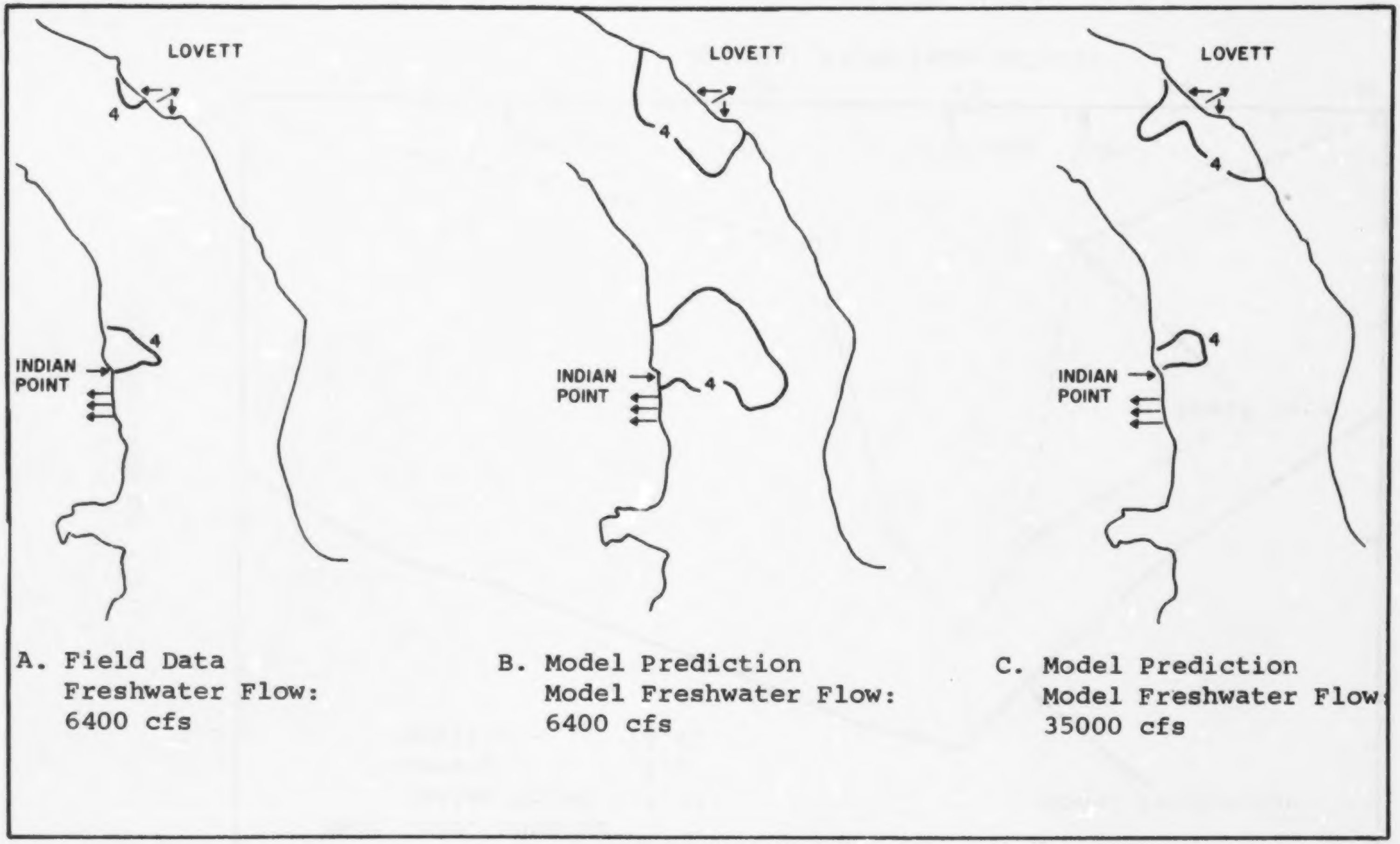
Figure 12. Comparison of Surface Isotherms of Flood for August, 1974 Survey


INDIAN POINT
5
4
3
3
INDIAN POINT
3
2
2

A. ARL PREDICTION (TEST Nº 13)
FLOOD (4th HOUR)
MODEL FRESHWATER FLOW : 20,800 CFS

B. ARL PREDICTION (TEST Nº 7)
FLOOD (4th HOUR)
MODEL FRESHWATER FLOW : 35,000 CFS

Figure 13. Model Test Results for the August, 1974 Survey with High Freshwater Flows


LOVETT
4
INDIAN POINT
4
LOVETT
4
INDIAN POINT
4
LOVETT
4
INDIAN POINT
4

A. Field Data
Freshwater Flow:
6400 cfs

B. Model Prediction
Model Freshwater Flow:
6400 cfs

C. Model Prediction
Model Freshwater Flow:
35000 cfs

Figure 14. Comparison of Surface Isotherm of HWS for August 24, 1974

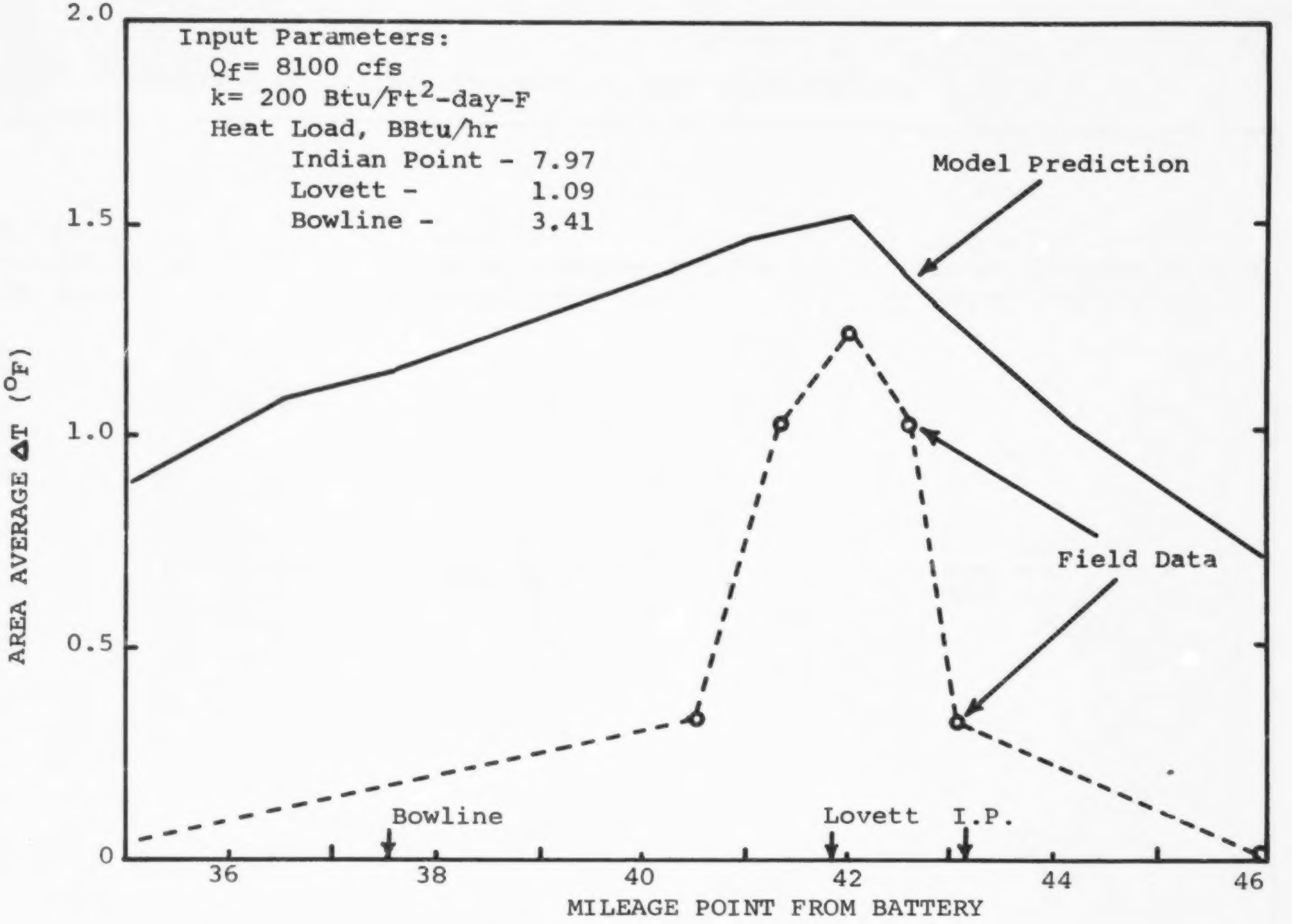


FIG.15 Average Excess Temperature August 20, 1974

15-45-10

IX-C-113

CASE STUDY: NEGOTIATION AND DEMONSTRATION DEVELOPMENT-
316A DEMONSTRATION TYPE II

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ABSTRACT

This paper describes the development of a 316a demonstration pursuant to section 316a of the "Proposed Effluent Limitations Guidelines and Standards for Steam Electric Power Plants." It describes the evolution of the demonstration delineating major decision points resulting from negotiations which spanned nearly two years. Finally, the paper summarizes the conclusion reached by the EPA as a result of their review of the data and their participation in numerous hearing pre-conferences.

INTRODUCTION

As a result of the publication by the USEPA of the proposed guidelines for power plants in March of 1974, an investigation was begun by the environmental department under my direction of the effects of thermal discharges from a 250 MW generating station located unfortunately just 5,000 feet downstream from a 650 MW generating station owned and operated by a different entity. Both stations discharged heated water from once-through cooling systems.

The study was initiated as the result of a condition of the draft NPDES permit from the regional EPA office requiring installation of cooling towers by July 1, 1977. The EPA Water Quality Office in Denver had initiated a site visit while assisting Region V of the EPA in the evaluation and catagorization of thermal emissions in Region V. They initiated negotiations with my office as a result of a determination that our client's plant was in a "water quality limiting situation" under state standards.

The first step was to develop cost studies for feasibility of once-through cooling for the generating station. These studies, the results of which are spoken to briefly in the text of the paper were the precipitator of decisions to pursue 316a exemption studies and defined the economic scope within which those studies were to be performed. Described herein is: 1) the regulatory foundation for 316a; 2) the developments resulting from plant operating and engineering data bases; 3) the developments resulting from dye studies and computerized thermal modeling of the discharge; 4) the results of the analysis and augmentation of biological data bases; and 5) the final stipulation of the agency, the utility operator, and their various consultants resulting from the numerous conferences prior to formal hearing proceedings.

THE REGULATION

As a brief recap the EPA issued "Proposed Effluent Limitations Guidelines and Standards for Steam Electric Power Plants" on March 4, 1974, they are a permanent part of 40 CFR 423. These standards were promulgated under the Federal Water Pollution Control Act of 1972 (Public Law 92-500).

Section 301(b) of the act requires "best practicable control technology currently available" (BPCTCA) by July 1, 1977, for all power plant effulents. By July 1, 1983, "best available technology economically achieveable"(BATEA) must be implemented. Section 304 of the act requires that the administrator of the EPA define BPCTCA and BATEA which he did in 40 CFR 423 March 4, 1974; that definition for thermal components being:

> "No discharge of heat except for cold side blowdown for all large base loaded units as reflected by the application of closed cycle evaporative cooling tower systems."

However, section 316(a) of the act gave utilities non-exempt for size or age reasons a means to seek relief from the stringent requirement of closed cycle cooling tower systems. 316a says that if the owner of a utility can demonstrate to the satisfaction of the regional EPA administrator that the thermal effluent limitation on his facility is "more stringent than necessary to assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on the body of water to which the discharges is to be made," that regional administrator may impose a different effluent limitation with respect to that thermal component.

On March 28, 1974, further amplified by discussion on October 8, 1974, the Federal Register proposed procedures for demonstrating applicability of alternative thermal effluent limitations. On September 30, 1974, the Water Planning Division, Office of Water and Hazardous Materials, EPA issued a "Draft 316a Technical Guidance Manual" to aid in the development of 316a demonstrations. This manual detailed three acceptable types of demonstration:

Type I) Proof of absence of "Prior Appreciable Harm"
Type II) Demonstrated protection of "Representative Important Species"
Type III) Submittal of significant "Biological, Engineering and Other Data"

It soon became obvious that there was no clear-cut delineation between presentation types and that regional policy would dictate direction. The biggest draw-back to Type I demonstrations being the apparent requirement for pre-operational data on the aquatic ecosystem of the receiving body of water. Few utilities prior to the implementation of the Federal Water Pollution Control Act of 1972 had developed ecosystem data bases, nor were they prepared for substantial programs to evaluate parallel unimpacted sites.

The Type II demonstration rested heavily on toxicity data developed primarily in laboratory experiments for species considered to be "important" it was clear that one of the parameters of "important" was that a species not be pollution tolerant but it was unclear whether "important" was couched in terms of importance to the ecosystem, importance to the economy, or importance as an indicator of a level of contamination. Therefore, most studies developed as a combination of existing data bases substantially augmented by in-situ data development; by engineering and other operational plant discharge data; by substantial computer simulation of expected alterations in discharge parameters; and by the application of these data to the laboratory data obtained on toxicology related to thermal parameters for selected species.

Although the generating station for which this demonstration was developed was exempt from EPA requirements for off-stream cooling, the Water Quality Office determined that off-stream cooling should be required for this station because it was in an area where USGS stream data indicated a violation of state water quality regulations for warm water fisheries. The utility was by definition operating in a "water quality limiting situation."

COOLING ALTERNATIVE CONSIDERATIONS

The first response to the order to implement off-stream cooling was, "What will it cost us?" To this end numerous studies were developed by the consultant. The first discussed engineering and economic implications of the following alternatives:

- Reduced Generation
- Recirculated Cooling Ponds
    - Atmospheric
    - Spray
- Flow-Through Cooling Ponds
    - Atmospheric
    - Spray
- Wet Cooling Towers
    - Natural Draft
    - Mechanical Draft
- Dry Cooling Towers
    - Direct
    - Indirect

This study considered relative requirements for cooling and make-up water, space and initial and operating capital among other parameters. Additional space requirements ranged from .9 acres for mechanical draft wet cooling towers to 400 acres for recirculating cooling ponds with atmospheric cooling and from $2.4 million in additional capital cost for flow-through cooling ponds with atmospheric cooling to in excess of $15 million for indirect dry cooling towers (some of which cost was related to the adaptation of existing turbines to the requisite high back pressure).

Selected economic comparisons are shown in TABLE I. It can be seen from the alternatives in the Table that capital costs would approach $3 million and be annualized in excess of $400,000 for any cooling system. With the addition of operating and maintenance costs the recirculated spray pond would create an additional annual burden on the utility of approximately $800,000 while the mechanical draft wet cooling towers would create an annual burden on the utility and its customers of an excess of $1,100,000.

It became apparent from this study that considerable monies could be expended in the pursuit of relief from these additional costs.

To this end, discussions were initiated with the Regional EPA office pursuant to application for 316a exemption, unfortunately, the EPA did not determine it to be in their best interest to relieve the utility from the requirements of the implementation schedule for cooling towers. Therefore, the utility was required to pursue the development of cooling alternatives and specifications for the selected alternative in parallel with 316a exemption studies, increasing the economic burden on the utility unnecessarily as indicated by the conclusions of this case study.

As a result of the initial meetings with the Regional EPA it was determined that the utility should study the implementation of partial cooling of the discharge. A comparison of alternative cooling systems for 25% off-stream cooling was developed. A summary of the systems illustrated in TABLE I is illustrated in TABLE II for 25% off-stream cooling. These alternatives all indicate annual increased operating burden to the utility and it's consumers of more than $250,000.

Another decision point also indicating the superior cost/benefit of pursuing 316a negotiations and demonstrations to their conclusion was therefore reached.

ENGINEERING AND OPERATING DATA

Analytical Thermal Analyses

The plant began commercial operation on March 31, 1970, with two units nameplated at 116 MW. The circulating water flow rate is 318 cfs with a design maximum temperature differential through the condenser of 15°F. Each of four pumps can be used to supply 87 cfs of cooling water. Each unit uses two condensers in parallel and a maximum water throughput of 159 cfs.

Normal operation indicates reduction to two pump operation October through May.

Dye Study

In order to arrive at the thermal plume sphere of influence, Rhodamine WT dye was released into the condenser cooling water discharge chamber. The plume resultant was photographed from the air, it was observed that the plume was deflected downstream by a sheet piling wall and that there was no strong horizontal mixing. The plume remained isolated in a portion of the split river channel. Due to the rapid diffusion of Rhodamine WT dye and its visibility in extremely minute concentrations it is assumed that the dye plume included the thermal plume beyond the limits of delineation of any reasonable thermal plume detecting device.

Thermal Plume Modeling

Thermal plume modeling has several limitations. Analytical models are primarily either near-field or far-field. A transitional area exists but has not yet been well defined by theoretical modeling. In the near-field the temperature decrease is primarily due to mixing influenced significantly by discharge channel configuration, flow, velocity, and temperature difference between the discharge and the receiving waters. In the far-field the temperature distribution is determined primarily by natural convection.

Two and three dimensional near-field thermal models are available. The discharge we were to model indicated inapplicability of three dimensional models due to the shall river depth during droughts limiting vertical entrainment of river water. A two dimensional model was selected since drought flow was one of the worst case situations we were interested in modeling, the discharge depth being nearly the same as the river depth. The two dimensional model chosen was formulated by Motz and Benedict and is limited by several assumptions including the following: 1) turbulent flow with entrainment; 2) negligible surface heat loss and 3) Gaussian normal temperature profiles.

In order to employ the model to determine temperature rise at any point downstream, initial temperature rise, equilibrium temperature of the receiving river, stream depth and velocity, and surface heat loss coefficients must be obtained. All are directly measureable with the exception of the equilibrium temperature and the surface heat loss coefficient.

In order to describe the river condition in those circumstances which represented extremes and were probabilistically unlikely to be found in a short study the following conditions were determined: 1) natural maximum river temperatures and 2) natural minimum river flows.

For initial modeling it was considered sufficient to consider the following five general cases of extreme conditions:

Case I
a) August average ambient river temperature = 27.9°C
b) Summer 7-day, 10-year drought flow (USGS) = 1100 cfs
c) Discharge = 319 cfs
d) Temperature rise above ambient (ΔT) = 9.1°C

Case II
a) Yearly 7-day, 10-year drought flow (USGS) = 700 cfs
b) September average ambient river temperature = 26.9°C
c) Discharge = 319 cfs
d) Temperature rise above ambient =9.1°C

Case III a) Yearly 7-day, 10 year drought flow (USGS) = 700cfs
b) October average ambient river temperature = 18.7°C
c) Discharge = 319 cfs
d) Temperature rise above ambient = 8.6°C

Case IV a) Yearly 7-day, 10 year drought flow = 700 cfs
b) October average ambient river temperature = 18.7°C
c) Discharge = 174 cfs
d) Maximum Δ T for October on record = 12.8°C

Case V a) Yearly 7-day, 10-year drought flow = 700 cfs
b) September average ambient river temperature = 26.9°C
c) Discharge = 159 cfs
d) ΔT = 9.8°C

Figure 1 is a reproduction of the results of the thermal modeling for case No. I.

Statistical Analysis of River Conditions

While the thermal plume modeling showed the anticipated results of worst case with a very restrictive assumption set it was necessary to develop the statistics indicating over the period of record how often these conditions might occur. Had the drought flow level been reached in concurrence with high river temperatures? Had these conditions ever been concurrent with scheduled maintenance outages which normally take place during the months of September and October? By comparing selected annual and summer low flows it was found that the flow of 700 cfs is exceeded more than 98% of the time from August to October and a flow of 1110 cfs is exceeded more than 98% of the time from June to August. By comparison, mean low flows for August were 3807 cfs and for September through October 2959 cfs with exceedence values of 45% and 65% respectively. It was determined from the statistical analyses that the concurrence of worst case conditions would be rare and could fail to occur in the remaining life of the plant.

This argument further supported the conclusion under negotiation with the agency that it would be imprudent to install cooling towers for the remaining life of the plant. Further, the base load use of the plant was anticipated to be less than the term of the permit. It was suggested that a serious consideration be made for reduction in generating capacity at critical times indicated by a measurement of actual river temperatures and flows.

An analysis ensued to determine appropriate envelopes for flow and temperature during which plant capacity would have to be reduced. Based on engineering and river data critical months for generation curtailment were reduced to summer high temperature months and the fall months of low flow. Obviously power reduction during mid-summer could be critical since this is a normal utility peak load period. Having determined from the physical characteristics of the plant when highest heat rejection was anticipated and from the physical characteristics of the river when lowest flows or highest ambient temperatures were predicted to occur, it remained to assess the plant operational effects on the ecosystem.

BIOLOGICAL DEMONSTRATION - TYPE II

By 1974, the state had designated representative important species. The EPA in their wisdom augmented the list adding "thermally sensitive" species.

It was our feeling that sufficient finfish studies had been done on the river by the other utility operator but that inadequate work had been done on other elements of the aquatic ecosystem to demonstrate diversity and balance. It was also felt that substantial chemical and water quality data should be taken for verification of prior reports. Finfish studies were performed as early as 1969, however they are difficult to correlate because in some cases no idea of species dominance or abundance is able to be drawn from the data and in others the location of collections or total number of finfish taken was not recorded. The most useable study occurred in 1973 and indicated low thermal preference of some species as well as velocity/temperature preferences for selected finfish in the receiving waters. Unfortunately available data on the thermal effects of representative species was incomplete in many cases and totally missing in others. Some typical examples are shown for finfish of concern in this study in TABLE III.

Since relative plume size and dilution effects are more a consequence of river discharge than plant discharge, the plume appears wider and longer in the fall than in the spring. It is anticipated that representative species of fish will either approach or avoid the plume and mixing zone according to their thermal preferences. Spawning in the river and in the discharge plume will also occur according to these preferences. Since the river naturally exceeds the minimum avoidance temperature level of some species found to exist in it is evident that adult fish are self-regulatory and adaptive in regard to their thermal environment. Because of this characteristic it became evident that our consideration of worst case situations rather than averages was appropriate.

Zeroing in on worst case considerations for the ecosystem it is appropriate to consider the minimum flow of the river at spawning time. This case is most critical to the perpetuation of the species as the fertilized eggs require certain temperature ranges and are not motile. The spawning range for most representative important species is March through August, the minimum flow for this period of time last occurred in 1941, and occurs on the average for seven days every twenty years and is more than one and one-half times the minimum 10-year 7-day low flow. It was found by reviewing summer temperature rises at the plant outfall that the thermal limit for carp, the most thermally tolerant species considered, would not be reached at any stage in its development. The effect on other considered species is speculative.

Much attention has been directed toward the biological effects due to thermal shock caused by plant cycling or operating interruptions. A substantial study showed that 99% of thermally shocked eggs hatched-86.1% normally. Further, the research indicated that as the eggs matured from their newly fertilized state they became less susceptible to temperature damage.

The most thermally intolerant species, the sauger, spawns in April and May in optimum water temperatures between 6°C and 14°C. The average temperature of the river is naturally higher than this in both of the months characteristic of sauger spawning. Apparently these fish have been able to spawn due to acclimation and there is no indication that an 8.3° rise above ambient would exceed the thermal limits of fertilized eggs during incubation or the thermal limits of developing fingerlings after acclimation. In other words, the biological data from the thermally intolerant species is inconclusive but nevertheless would limit the months of concern to April and May.

CONCLUSION

The data was in. Negotiations became more frequent and more intense as the formal hearing date approached with the hopes of settling the issue in prehearing conferences. It was obvious that the utility should not be asked to lower natural river temperatures, and that very few months were of concern to the aquatic biota. It was also obvious that the probability of conccurance of high river temperatures and low river flows were limited and that the base loaded life of the plant was to be foreshortened by the development of substantial additional generation within the utility's system. The problem became one of finding a sure way to predict or measure these periods of impending problems for which some action should be taken.

In the final analysis it was determined that a monitor should be placed at a predetermined distance downstream from the plant analagous to a mixing zone and that based on feedback from this monitor, plant capacity should be curtailed during those circumstances defined to be critical to the ecosystem. The curtailment program was scaled to increase as the term of the permit progressed, from 5% in 1976 to 25% in 1979 and was limited in operation to 1 July through 15 October.

The statistics indicate that the utility may never have to reduce generating capacity during the useful life of the plant as a result of an ecological emergency. The units will be relegated to cycling operation by the end of the permit term. The agency reached a conclusion based on the data, yet provided for the protection of the ecosystem should probabilistically unlikely circumstances occur. Engineering and legal expenses considered, both the causes of the ecosystem and cost-effective power generation seem to have been reasonably served by this conclusion.

TABLE I

Comparative Costs for Full Off-Stream Cooling

Cooling System	Equipment Capital Cost	Annual Operating and Maintenance Cost	Total Annualized Cost
Once-Through	----	$423,000	$423,000
Recirculated Spray Pond	$3,011,100	$806,000	$1,225,000
Mechanical Draft Wet Tower	$2,852,500	$1,136,000	$1,561,000

TABLE II

Comparative Costs for 25% Off-Stream Cooling

Cooling System	Equipment Capital Cost	Annual Operating and Maintenance Cost	Total Annualized Cost
Once-Through	----	$111,480	$111,480
Recirculated Spray Pond	$866,000	$207,230	$336,260
Mechanical Draft Wet Tower	$976,000	$299,890	$445,310

TABLE III

Finfish Thermal Tolerance

	Spawning (C)	Maximum Embryo Survival Temp. (C)	Growth (C)	Maximum for Juvenile Survival (C)
Catfish	27	29	32	36
Largemouth Bass	21	27	32	34
Sauger	10	21	25	--
Carp	21	26	--	--

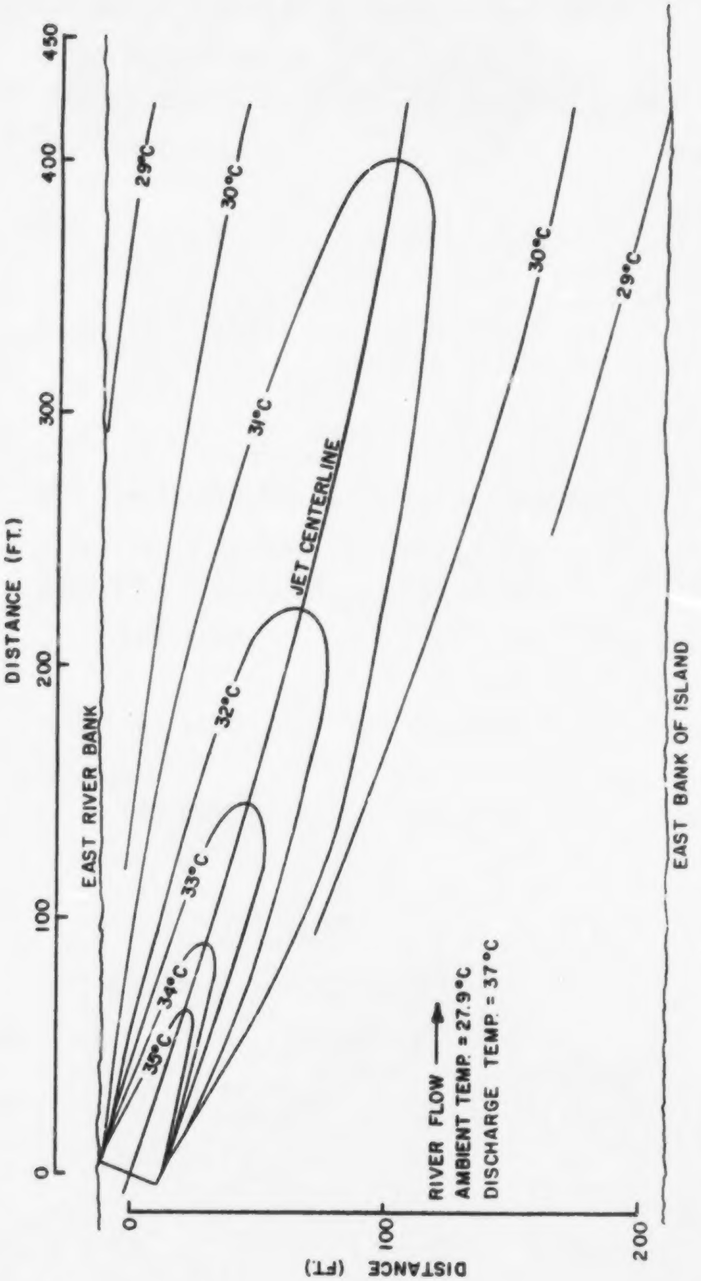
DISTANCE (FT.)
0
100
200
300
400
450
EAST RIVER BANK
EAST BANK OF ISLAND
29°C
30°C
31°C
32°C
33°C
34°C
35°C
JET CENTERLINE
30°C
29°C
RIVER FLOW →
AMBIENT TEMP. = 27.9°C
DISCHARGE TEMP. = 37°C
0
100
200
DISTANCE (FT.)

Figure 1

SESSION X-A
UTILIZATION VI

16-45-23

X-A-3

WASTE HEAT UTILIZATION FOR DEWATERING SEWAGE SLUDGE

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ABSTRACT

Since 1925, the Jones Island Wastewater Treatment Plant has dewatered Activated Sewage Sludge in rotary kiln dryers to produce a commercial grade fertilizer. Prior to December of 1974, ambient air was forced into the dryer combustion chamber and heated to approximately 1600°F, utilizing fuel oil or natural gas, to provide the heat required to dry the Sewage Sludge. In December of 1974, the Plant placed into service a waste heat utilization system using the exhaust gases from a 16 MW gas-oil turbine generator to provide the majority of the heat required to dry the Sewage Sludge. The paper describes the dryer and turbine modifications made to utilize the waste exhaust gases as drying air for the ten (10) existing rotary dryers producing 200 tons of dry solids (Milorganite) per day. Two years of operational experience is discussed and confirms the design expectations to reduce total energy consumption at the plant by 20%. The waste heat utilization feature has proven to be a reliable marriage of an electrical generation system to a Sewage Sludge drying system. The operational and maintenance experiences, which are discussed in the paper, show that maximum efficiency in utilization of the waste gases can be accomplished in a process stream which is a continuous around the clock operation.

INTRODUCTION

The Sewerage Commission of the City of Milwaukee operates and maintains the 200 MGD (757,000 cu m/d) Jones Island and the 120 MGD (454,000 cu m/d) South Shore Activated Sludge Wastewater Treatment Plants which provide service to the City of Milwaukee, the suburbs in the District surrounding the City of Milwaukee, and on a contract basis, several other fringe municipalities within the watershed boundaries. The scope of this paper relates to the utilization of the waste exhaust gas from a gas turbine to provide combustion air for large rotary dryers to dewater waste activated sewage sludge. This match up along with other improvements were successful in producing significant energy conservation at the Jones Island plant as follows:

1. Recovery of exhaust heat which supplies approximately 70% of the heat required for dryer operation.
2. Overall plant fuel usage was reduced 20%.
3. Reduction of energy requirements by replacement of obsolete equipment.

The Jones Island Wastewater Treatment Plant - History

The Jones Island Wastewater Treatment Plant began operation in 1925 as an activated sludge plant with a sewage treatment capacity of 85 MGD. The method of waste sludge disposal was to produce a fertilizer product because of the high organic nutrient value of the finished product. This fertilizer is a commercially-sold product called Milorganite, and is familiar to many, and is still produced today at the Jones Island Plant.

Its production involves the dewatering of the waste sludge solids from the Purification Plant by various chemical and mechanical steps. The waste sludge solids of approximately 1.5 to 2% are conditioned with chemicals to aid in filtration. Filter cake generated by vacuum filters of approximately 15% solids (85% moisture) is then fed to large, rotary kiln-type, direct-, in-direct dryers. The dryers reduce the end product moisture to produce a granular product that has the appearance of coffee grounds after selective screening. Fig. 1 is a plan of the Jones Island Plant and fig. 2 is a schematic showing the relationship of the dryers to the overall process.

The purification and sludge dewatering plants are continuous, 24-hour-a-day operations and require a constant power supply of a high degree of reliability. When the plant was originally designed prior to 1925, a coal-fired power plant was provided to meet the large quantity of low pressure process air, electric power, and process steam for miscellaneous services. The conventional coal-fired steam power plant included steam turbine-driven centrifugal compressors and electric generators to meet these basic requirements. Steam energy was also provided for large steam-driven reciprocating vacuum pumps, plant heating and other plant processes.

The wastewater treatment plant was expanded to meet the growing population and service area, first in 1935, and again after World War II in 1952. These two (2) major expansions in addition to the Original Plant provided a Purification Plant capability of 200 MGD and a Dryer Plant fertilizer production of 70,000 tons per year.

The energy source for both power generation and heat drying has always been dictated by costs. The original source-coal-was converted to coke oven gas in 1950, and most recently, in 1960, natural gas, with fuel oil for standby. Fig. 3 is a schematic of the Original Plant energy cycle using natural gas as fuel.

Electrical and Mechanical Modernization

The original Power Plant electrical generation and related distribution facilities were increased when plant expansions were made in 1935 and 1952, but were not upgraded in keeping with the state of the art. Consequently, the maintenance of these areas were becoming more difficult and their further expansion impractical.

In 1967, Engineering Consultants were retained to review the plant power system. Their complete study of the current and projected power requirements of the entire treatment facility concluded that the antiquated power generating and electrical distribution facilities be replaced.

In view of the continuous heat requirements in the sludge drying plant, the study concluded that the best power facility would be gas turbine-driven electric power generators and turbine waste heat utilization in the existing sludge dryers. The decision was influenced by the availability of low cost natural gas, the desire to assure the plant of an uninterruptable power supply, and the obvious need for a complete new electrical power system in the plant.

Based on the studies made, and the inherent need to provide continuous service during the period of construction, the following steps were taken:

1. Proceeded with engineering design of the plan covering gas turbine generators with heat recovery, and purchase of the major long-term delivery equipment, such as gas turbines, generators, axial flow compressors, metal-clad primary switchgear, secondary unit substations, process air piping, and large synchronous motors as soon as the engineering design provided the required data.
2. Replacement of the obsolete steam engine-driven vacuum pumps with new induction electric motor-driven two-stage vacuum pumps. Replace the associated obsolete switchgear and motor control equipment in the area with new secondary unit substations and modern electrical equipment.
3. Build the new Power House with two (2) 16 MW gas turbines and recover the exhaust heat which will supply 70% of the heat required to dry the Milorganite fertilizer.
4. Build the new Compressor Building with four (4) axial flow air compressors and their synchronous motor and gear drivers. Install the metal-clad switchgear in the Compressor Building for control of the synchronous motors.
5. Phase out existing obsolescent steam-driven equipment in the old Power House consisting of steam turbine-driven generators and process air compressors, generator switchboard, and generator air circuit breaker equipment as soon as the new replacement equipment in the new Power House and new Compressor Building is ready to be placed in service.
6. Install a modern central control room in the new Power House to monitor and control important plant functions throughout the complete plant area.

The major items of equipment provided in the Electrical and Mechanical Modernization Program are listed in Table 1.

Gas Turbine Concept - Waste Heat Utilization

The matching of the Gas Turbine Exhaust to the dryer furnace air requirements was the key to the successful merger of these two (2) proven systems. Theoretically, the two (2) appeared to blend together, but actual operation must be flexible to cope with the varying characteristics of the continuous drying process. Therefore, independent tests were made on the dryers to determine their full range of compatibility with and without preheated air. With the results of tests run on ambient air, projections of burner modification were made to handle 900 F combustion air (gas turbine exhaust). In addition, criteria was established to provide for operation of the new burners on fuel oil as well as natural gas for both ambient air and waste heat operation.

Fig. 4 schematically shows the in-puts and out-puts of the original dryer system. Ambient air and natural gas fuel burned in the furnace section at 1700 F is tempered down to 1200 F heated air along the length of the rotary dryer. Inside the dryer it comes in direct contact with wet filter cake and previously dried material. Dryer gases are then exhausted to cyclone separators while the granular dry finished product is classified by screens and stored for future shipment.

Fig. 5 shows the combination of the gas turbine and dryer systems. The heated air to the dryer is now produced by gas turbine exhaust of 900 F tempered up to 1200 F. The other in-puts and out-puts of the dryer remain as before.

The potential supply of excess turbine exhaust gas over and above the amount that could be utilized by the dryers in service justified the provision of waste heat recovery boilers. These boilers can provide a portion of the process steam required for heating and other miscellaneous plant services. Fig. 6 is a schematic of the total new plant energy cycle.

Installation and Operating Experience

The installation, check-out and phasing into operation of all the new equipment took considerable coordination between the contractors and the plant operational personnel. Unlike a new plant or a normal process installation which could be shut down, the Jones Island Wastewater Treatment Plant purification and sludge processing facilities is a continuous daily operation. As such, the installation of the new equipment had to be accomplished with no or minimum interruption of the existing plant facilities. The first part of the installation, starting late 1970, involved the replacement of the steam-driven vacuum pumps with motor-driven vacuum pumps. Initially, one motor-driven vacuum pump was installed and operated in parallel with one steam-driven vacuum pump. This allowed the removal of two (2) steam-driven vacuum pumps and the installation of five (5) new motor-driven vacuum pumps.

As this part of the installation was proceeding, the new primary 13.8 kv electrical distribution system was being installed to operate in parallel with the old 480-V electrical system. The new 13.8 kv primary electrical distribution system was fed from a new 20,000 kva tie-in line from the

Wisconsin Electric Power Company without a backup since the installation of the gas turbines was in process. Because potential interruptions of the new power supply was possible, it was felt that the safest operation was to have critical loads tied into the old power system where backup protection was still available. Numerous electrical connections had to be made under "HOT" conditions to keep the plant equipment in service.

By December of 1973, the four (4) new process air compressors were ready to be put in service. The new compressors capable of delivering 110,000 scfm (3100 c um/m) at 10 psig (7030 g/scm) are powered by 5500 hp, 4,160 v synchronous motors. The synchronous motors were selected for this application to provide improved power factor correction within the plant. Again, considerable coordination between plant operations and the contractor had to be accomplished for the final tie-in of the low pressure air headers into the existing air headers to continuously provide air for the secondary activated sludge plant.

In April of 1974, the gas turbines were ready for on-line testing and check-out. The gas turbine manufacturer conducted a three-day in-plant Operator's Training School. None of the power plant operators had previous gas turbine experience and therefore, it was essential that the Operators obtain the basic fundamentals of gas turbine operation. The in-plant training was preferred because it enabled the operators to associate the particulars of a gas turbine directly with the two units they would be operating. The training school for the operators outlined the principles of gas turbine operation, the sequence of operations, the responsibilities of the operator, and the basic maintenance guidelines.

It should be pointed out that this gas turbine application, in itself is unique. There are no ducts extending vertically from the units and also the units, even though totally within a building, are still completely lagged as can be seen in Fig. 7. This has two advantages: First, the maintenance of the unit can be performed utilizing the overhead cranes without dismantling the discharge ducts and, second, the lagging provides sound and heat protection for the operators and maintenance personnel. The actual air inlet and discharge ducts are connected to the bottom of the turbines. The turbine waste exhaust gas is ducted directly to the atmosphere or to a variable diameter main waste heat distribution duct where it is maintained under constant pressure for further distribution duct where it is maintained under constant pressure for further distribution. Generally, no exhaust gas is vented to the atmosphere. Fig. 8 shows the main waste heat distribution duct and the vertical ducts feeding the waste heat to each of the ten (10) dryer furnaces. Excess waste heat from the main waste heat distribution duct is also fed to the inlets of two (2) 14,000 lb/hr. (6,350 kg/hr) waste heat recovery boilers which are depicted in Fig. 9.

Through a sequence of closing or opening guillotine dampers, butterfly valves, and automatic modulating valves, the waste heat can be directed to dryer furnaces, the waste heat recovery boilers, or the atmosphere.

After the in-plant training school was finished, the gas turbines were put into operation to provide the much needed backup electrical generation. The exhaust gases, ranging up to 950 F, (510 C) were temporarily discharged to the atmosphere. Meanwhile, construction continued on the waste heat distribution duct system.

In order to utilize the waste heat, the ten (10) dryer furnaces had to be modified. Each dryer originally had a forced draft fan which took outside air, inside air, or a blend of both and fed it to the dryer gas burner. To prepare the dryers for utilization of a maximum amount of turbine exhaust gas, the original forced draft fans had to be removed and the furnace had to be completely sealed to prevent infiltration of ambient air into the dryer furnace. Each dryer was taken out of service for approximately one month for these modifications and the installation of new burner assemblies and the vertical ducts from the main waste heat distribution duct. Since it was impossible to put waste heat into the main waste heat distribution duct while the dryer modifications were proceeding, and since the treatment plant could not operate adequately without at least nine (9) of the ten (10) dryers in service continuously, two (2) large 85,000 cfm (670,000 cu cm/m) forced draft fans were used to pressurize the main waste heat distribution duct with outside air to enable a dryer to be put back into service after it had been modified. These fans have since been removed and air inlet door have been provided at each burner to permit the dryers to be operated on induced air, if problems develop with the gas turbines and the pressure from the turbine exhaust is lost in the main waste heat distribution duct.

By December of 1974, the main waste heat duct installation and the dryer modifications were completed. It was now time to blend the two (2) systems together and prove out the original design concept. The first step was to check out the effects the waste heat would have on the main waste heat distribution duct. This was accomplished by gradually bleeding waste heat into the duct and building up the duct temperatures. During the initial heating when the duct temperature reached 500 F (260 C), smoke began to emanate from the duct work. The waste heat was immediately removed from the duct and the ensuing investigation revealed that the binder in the duct insulation was burning off, causing the smoke. After being assured by the insulation supplier that loss of the binder would not reduce the insulating characteristics of the insulation, we resumed heating of the main waste heat distribution duct. This time the heating process was accomplished without any detrimental effects to the duct or insulation. As previously indicated for proper distribution of the waste heat to the dryer furnaces, the main waste heat distribution duct had to be pressurized, so after the duct was heated the pressure controller was adjusted and calibrated. For normal operation with all ten (10) dryers and the two (2) waste heat recovery boilers in service, the duct pressure is maintained at four inches (4 in.) (10.2 cm) of water. If, for some reason, the duct pressure would exceed four inches (4 in.) (10.2 cm), the pressure controller automatically opens a modulating leaf damper and exhausts waste gas to the atmosphere. To-date, this controller has proven to be a safe and reliable system. After the successful heating of the main waste heat distribution duct, the dryers were put into service utilizing waste heat. The dryers were checked for operation with and without waste heat feed. It was determined that the dryer could be started in various modes. The dryer could be brought up to the control temperature of 1200 F (649 C) by gradually feeding waste heat to the dryer and once maximum heat was obtained from the waste heat, the gas burner would come into service and finish heating the air. The dryers could also be brought up to the control temperature of 1200 F (649 C) by opening a door in the side of the burner box, where induced air can enter the furnace to be heated. After the control temperature has been reached, the gas flow is shut off, the door is shut, and full waste heat is applied to the dryer. The controller then automatically brings the gas burner back into service to bring the heat up to 1200 F (649 C). Both methods work satisfactorily and operator preference dictates which method is used. The operators play a significant role in the overall operation of the dryers with waste heat. A negative pressure of 0.1 (.25 cm) to 0.2 (.51 cm) of water has to be maintained within the combustion chamber to prevent hot gases from escaping through cracks into the furnace brickwork cooling passages. In addition, he has to control the opening of the butterfly valve through which the waste heat is fed. If the valve is opened too fast, the flame on the gas burner can be blown off, and thereby forcing a complete purge of the system before re-igniting the burner. The built-in safety features in the gas burner control system and in the main waste heat distribution duct pressure controller have proven to be very reliable. It should be indicated that now, when we have trouble with a dryer, we can't just instruct the operator to "kill the fire" which in the past meant turning off the gas flow to the dryer. Now, he is instructed to "kill the fire and shut the butterfly valve."

With the dryers operating satisfactorily on waste heat, we turned our attention to the waste heat recovery boilers. Since these boilers were designed and constructed for this purpose, little problems were encountered in bringing them on-line.

More than two years have now elapsed since this complete system was put into service. Overall, we are very well pleased with the operation and the resultant energy savings; however, the system has not been totally fool proof. When the gas turbines were initially put on line, we required the operators on each shift to fill out a problem report, itemizing problems they had with the gas turbines, compressors, waste heat duct, etc. This was intended to provide a continuity of communications between the plant operational personnel, the design engineers and the contractors, so that problems could be immediately identified and corrected. The system proved to be very helpful. It was started on July 3, 1974 and was intended to be used for only thirty (30) days. It was finally discontinued during January of 1976, approximately eighteen (18) months longer than its original intended use. The report did prove to be very useful and numerous small problems were solved. Some of the major problems, which were encountered were:

1. Cracking of joint welds in the waste heat exhaust duct;

2. Premature failure of the waste heat exhaust duct expansion joint boot material;
3. Warping of the guillotine dampers;
4. Oil leaks in the horizontal joint of the turbine pedestal bearings;
5. Settings for proper closing of the motorized butterfly valve operators;
6. Nuisance alarms on the Gas Turbine controls; and
7. Single guillotine dampers in the heat duct to the Waste Heat Boilers.

The causes of these problems varied from improper design, faulty shop fabrication and faulty field installation. The cracks in the joint welds of the waste heat duct were caused by improper shop welding techniques and were corrected by the contractor in the field. The premature failure of the expansion joint boot material was due to a supplier furnishing a material which did not meet original specifications. The boot material was subsequently, replaced by the supplier, however we have now found out that even the material as specified has a short life of less than fourteen (14) months and we are now looking for a new material. The oil leaks in the horizontal joint of the turbine pedestal bearings was caused by poor shop machining techniques and has since been corrected by the contractor. The motorized butterfly valve operators were field set for closing prior to heating of the waste heat duct. We have now found that the settings must be rechecked annually to maintain a good seal when the valve is closed. The nuisance alarms on the gas turbine controls is still a problem and work is continuing with the manufacturer to find a solution. So far, it has not been a detriment to the operation. The single guillotine damper in the heat duct to the waste heat boilers is a design shortfall which prevents us from isolating a waste heat boiler as long as the heat duct is pressurized with hot exhaust gas. We will be directing future modifications towards a double damper system with an air purge to provide a positive shutoff in the heat duct to the waste heat boilers.

Operational experiences have shown that communications between personnel in plant operations, maintenance and engineering was very important to the successful merger of these two proven systems and is still very important to the successful day to day operation of the complete system. We look forward to years ahead of continued energy savings and reliable operations.

Energy Consumption - Old vs New Power Plant

The total plant fuel consumption comparing the 1965 to 1970 average to the 1975 utilization was reduced from 7.65 million cfd of natural gas (216,000 cu m/d) (78,800 therms/day) to 6.09 million cfd (172,300 cu m/d) (62,700 therms/day). Although the power plant fuel consumption was increased 28% from 3.90 million cfd (110,400 cu m/d) (40,200 therms/day) to 4.98 million cfd (139,000 cu m/d) (51,300 therms/day) because of the power requirements of the increased average process air (increased over 17%) and vacuum pump capacity. However, the dryer plant fuel consumption decreased 70% from 3.75 million cfd (106,000 cu m/d) (38,600 therms/day) to about 1.12 million cfd (31,700 cu m/d) (11,500 therms/day). Table 2 lists daily average gas consumption from 1965 through 1976. The before-and-after effect of the modernization program can be appreciated by comparing 1970 and 1975 which indicates the total overall plant gas consumption has been reduced by 20%.

The energy conservation as employed was very timely in relationship to the cost and availability of natural gas. As previously indicated, the cost of natural gas during the initial design stage of 1967-68 was approximately 4.5¢/therm whereas the most recent cost was 17.55¢/therm for the month of February 1977. Table 2 includes the cost of natural gas.

The design of the facilities provided the flexibility to internally generate power or purchase all power during periods when natural gas was not available for use. Also, the turbines and dryers can operate utilizing fuel oil. The mode of operation is dictated by economics and at the present time, the most economical mode is utilization of natural gas for power plant and dryer operation.

Summary

1. The combination of the gas turbine and dryer energy sharing concept represents a practical and successful merger of two (2) proven heat energy systems. The flexibility of operation permits continuous reliable operation of the dryers with or without the turbine exhaust gas.
2. The efficiency of the combined cycle met predicted levels and reduced the fuel required for dryer operation by 70% and overall actual fuel consumption was reduced by 20%.
3. The system is inherently safe because the dryers are normally at a negative pressure condition and consequently impose no detrimental back pressure on the gas turbine or connecting duct work. The system is completely sealed and thoroughly insulated. In addition, pressure sensitive devices dump the exhaust gases in the event of excessive back pressure to protect the system.
4. Credit for success of this accomplishment must be shared with the plant operating personnel. Without their experience over the years and their attention to the new equipment as it was put on-line, the capability of this working system may not have been realized to its present extent.

Acknowledgements

The authors of this paper would like to acknowledge the cooperation and assistance of all the personnel who had a part in making this system a success. Particular acknowledgement is given to:

1. Robert J. Borchardt, Chief Engineer and General Manager
   Metropolitan Sewerage District of the County of Milwaukee
2. Ray D. Leary, Retired Chief Engineer and General Manager
   Metropolitan Sewerage District of the County of Milwaukee
3. Black and Veatch Consulting Engineers, Kansas City, Missouri
   William R. Call, Project Manager

TABLE 1

MAJOR EQUIPMENT

ELECTRICAL and MECHANICAL MODERNIZATION PROGRAM

Power House

Quantity	Description	Size
2	Gas Turbines	16,000 kW each
2	Electric Generators	20,000 kVa each
2	Waste Heat Boilers	14,000 lb/hr
2	Fired Package Boilers	23,000 lb/hr
1 lot	Electrical Switchboard	9 sections
1	Tie Controller	
1	Turbine Console	
1	Plant Supervisory Central Control Console	
2	Iso-synchro Controllers	
1	Secondary Unit Substation	2,000 kVa
1	Motor Controller Substation	2,000 kVa
2	Fuel Gas Booster Compressors	2,200 psig, 900 hp
1	De-Aerator	
4	Motor Control Centers	
2	Static Exciters	
2	Ground Reactor	
1	Water Conditioning System	
2	Inlet Duct Systems for Gas Turbines	Cor-ten
2	Inlet Silencers	Cor-ten
2	Hot Exhaust Duct Systems for Gas Turbines	410 S.S.
4	Hot Exhaust Silencers	409 S.S.
2	Control Air Compressors	
1 lot	15 kV Switchgear	13 sections
1	Battery, 24 volts, dc	620 ampere

Compressor Building

Quantity	Description	Size
4	Axial Compressors with Inlet Guide Vanes	110,000 scfm each
4	Synchronous Motors	5,500 hp

TABLE 1 - continued

Quantity	Description	Size
4	Transformers (captive)	5,000 kVa
1 lot	5 kV Metal-clad Switchgear	8 sections
2	Motor Control Centers	
2	Control Air Compressors	
5	Rollo-matic Air Filters	
4	Agglomerators with Bag Filters	
2	Silencers (East and West Plant Air Headers)	
4	Inlet Silencers for Axial Compressors	
4	Lubrication Consoles	

The following major pieces of equipment, as part of this project, have been installed in existing buildings:

Quantity	Description	Location
6	Vacuum Pumps, 5,600 acfm 1.0 inches hg, abs, each	Machinery Bay
6	Motors for Vacuum Pumps, 250 hp each	Machinery Bay
1	Secondary Unit Substation, 4,000 kVa	Machinery Bay
1	Remote Supervisory Control Station	Machinery Bay
1	Secondary Unit Substation, 2,000 kVa	Old Power House
2	Motor Control Centers	Old Power House
2	Cooling Water System Pumps and Motors 3,000 gpm each	Old Power House
10	Dryer Furnaces, New Burners	Dryer House
2	Motor Control Centers	Dryer House
1	Secondary Unit Substations, 2,000 kVa	Return Sludge Building
1	Remote Supervisory Control Station	Return Sludge Building
1	Remote Supervisory Control Station	East Plant

TABLE 2

NATURAL GAS CONSUMPTION

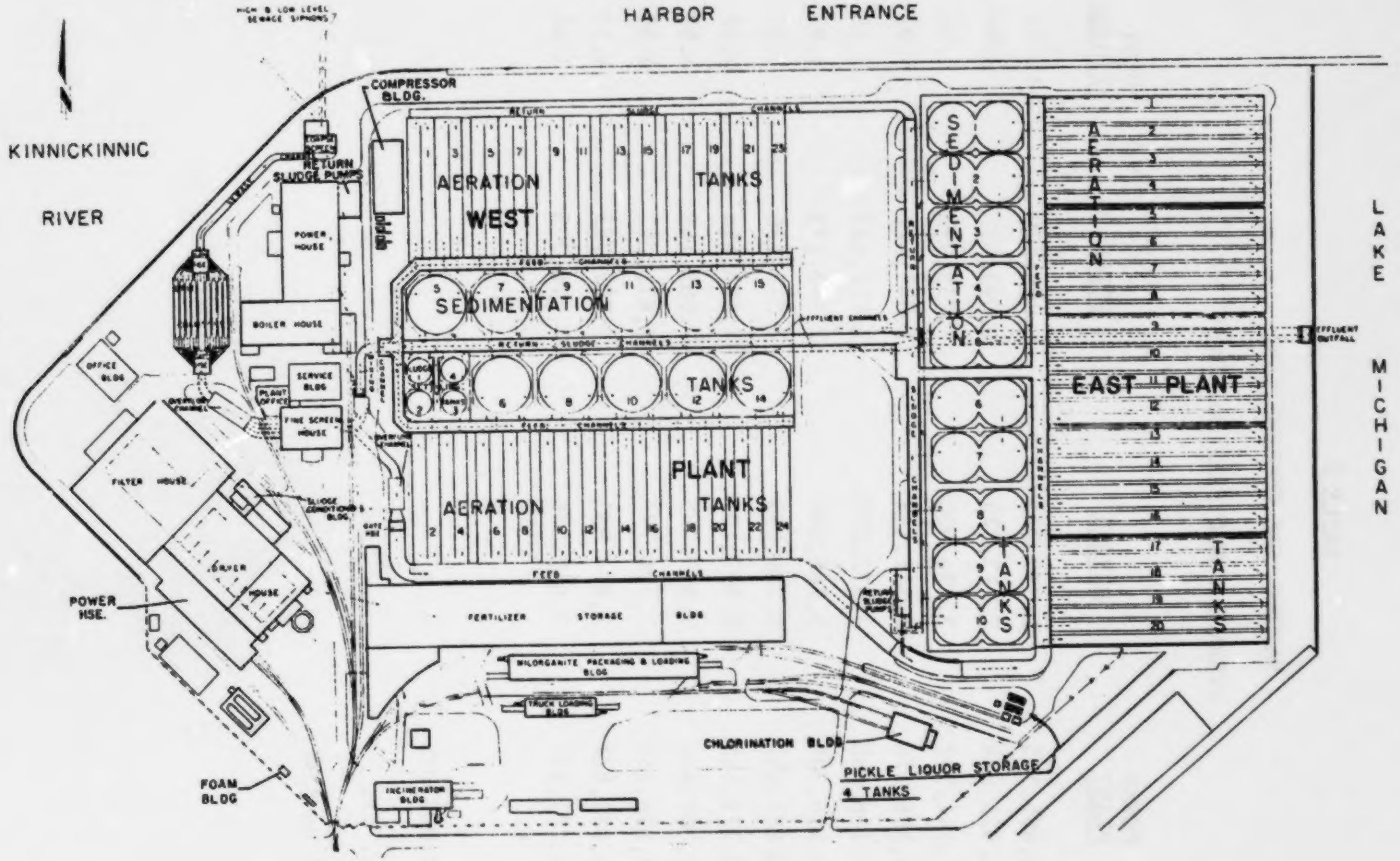
AVERAGE CUBIC FEET per DAY

	POWER PLANT	DRYERS	TOTAL	COST ¢/Therm
1976	4,895,545	1,370,725	6,266,270	12.08
1975	4,975,804	1,117,823	6,093,627	8.99
1974	4,341,952	3,394,000	7,735,992	6.42
1973	4,588,174	3,347,448	7,935,622	5.92
1972	4,486,880	3,332,535	7,819,415	5.38
1971	3,916,505	3,766,668	7,683,173	4.83
1970	3,887,041	3,709,095	7,596,136	4.83
1969	3,976,515	3,669,101	7,645,616	4.68
1968	4,007,404	3,875,765	7,883,169	4.52
1967	3,876,246	3,794,795	7,671,041	4.50
1966	3,882,821	3,824,932	7,707,753	4.53
1965	3,772,439	3,642,356	7,414,795	4.48

1 Therm = 100,000 BTU

= 1020 BTU/cu. ft.

1 cfd = .0283 cu m/d


HARBOR ENTRANCE
KINNICKINNIC RIVER
LAKE MICHIGAN
HIGH & LOW LEVEL SEWAGE SIPHONS
COMPRESSOR BLDG.
RETURN SLUDGE PUMPS
POWER HOUSE
BOILER HOUSE
SERVICE BLDG
PLANT OFFICE
FINE SCREEN HOUSE
OFFICE BLDG
OVERFLOW CHANNEL
FILTER HOUSE
SLUDGE CONDITIONING BLDG.
GATE HSE
DRYER HOUSE
POWER HSE.
FOAM BLDG
INCINERATOR BLDG
AERATION TANKS
WEST PLANT
SEDIMENTATION TANKS
RETURN SLUDGE CHANNELS
FEED CHANNELS
FERTILIZER STORAGE BLDG
MILORGANITE PACKAGING & LOADING BLDG
TRUCK LOADING BLDG
CHLORINATION BLDG
PICKLE LIQUOR STORAGE
4 TANKS
EFFLUENT CHANNELS
EFFLUENT OUTFALL
RETURN SLUDGE PUMPS
EAST PLANT

Jones Island Waste Water Treatment Plant
FIGURE 1

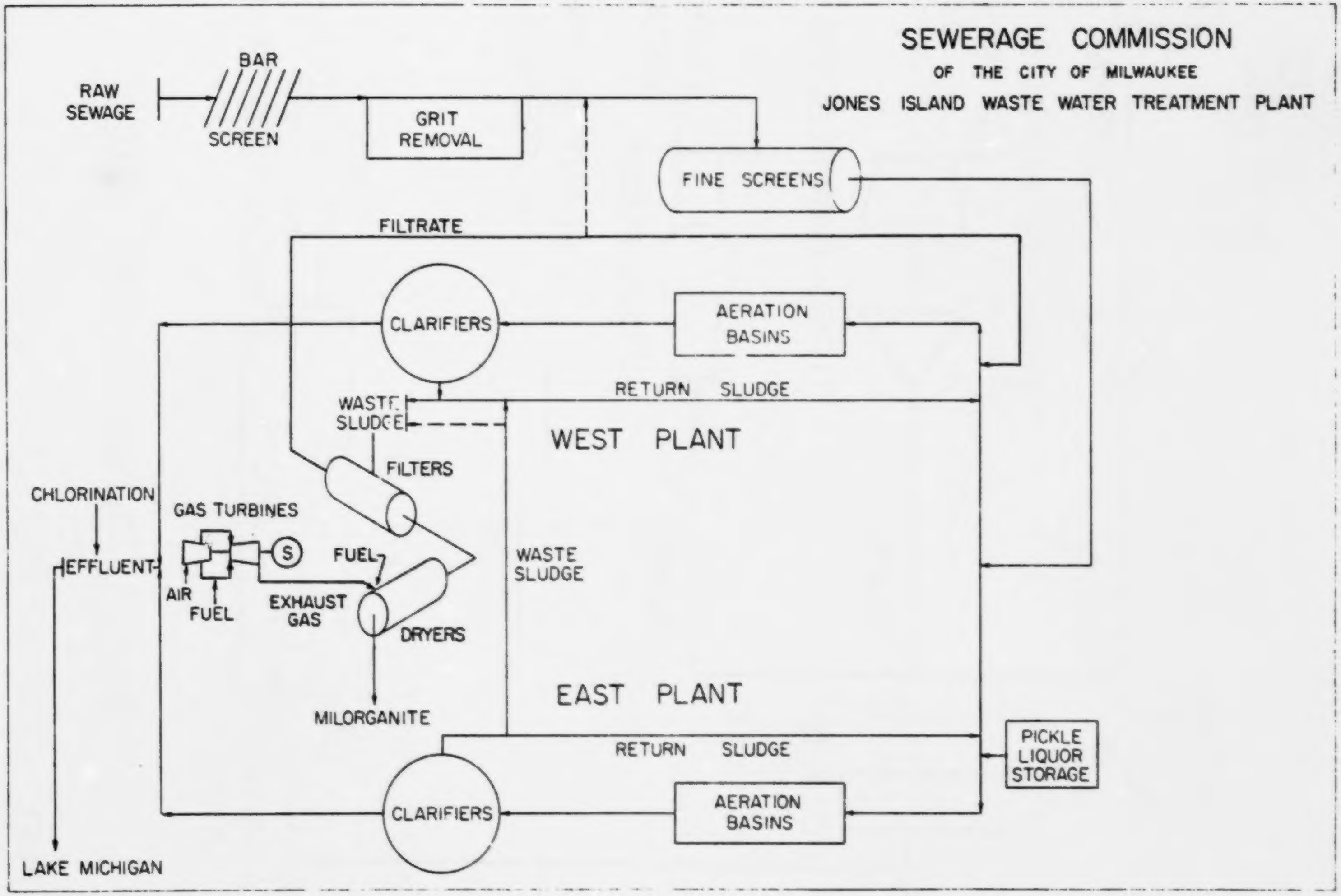
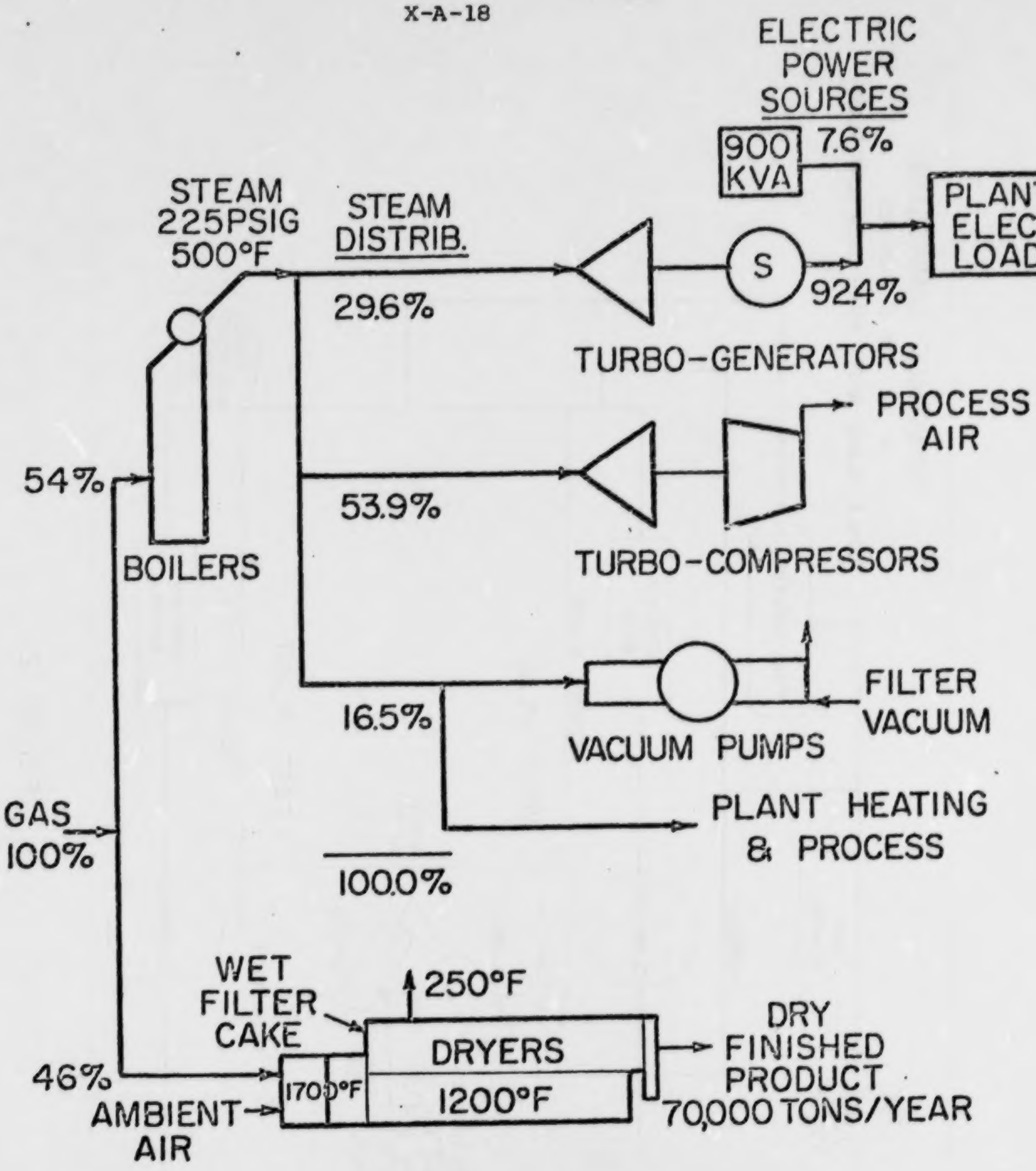

SEWERAGE COMMISSION
OF THE CITY OF MILWAUKEE
JONES ISLAND WASTE WATER TREATMENT PLANT
RAW SEWAGE
BAR SCREEN
GRIT REMOVAL
FINE SCREENS
FILTRATE
CLARIFIERS
AERATION BASINS
RETURN SLUDGE
WASTE SLUDGE
WEST PLANT
FILTERS
CHLORINATION
GAS TURBINES
S
FUEL
EFFLUENT
AIR
FUEL
EXHAUST GAS
DRYERS
WASTE SLUDGE
MILORGANITE
EAST PLANT
RETURN SLUDGE
PICKLE LIQUOR STORAGE
CLARIFIERS
AERATION BASINS
LAKE MICHIGAN

FIGURE 2


ELECTRIC POWER SOURCES
900 KVA
7.6%
PLANT ELEC. LOAD
S
92.4%
STEAM 225PSIG 500°F
STEAM DISTRIB.
29.6%
TURBO-GENERATORS
PROCESS AIR
54%
53.9%
BOILERS
TURBO-COMPRESSORS
FILTER VACUUM
16.5%
VACUUM PUMPS
GAS 100%
PLANT HEATING & PROCESS
100.0%
WET FILTER CAKE
250°F
DRYERS
DRY FINISHED PRODUCT
46%
1700°F
1200°F
AMBIENT AIR
70,000 TONS/YEAR

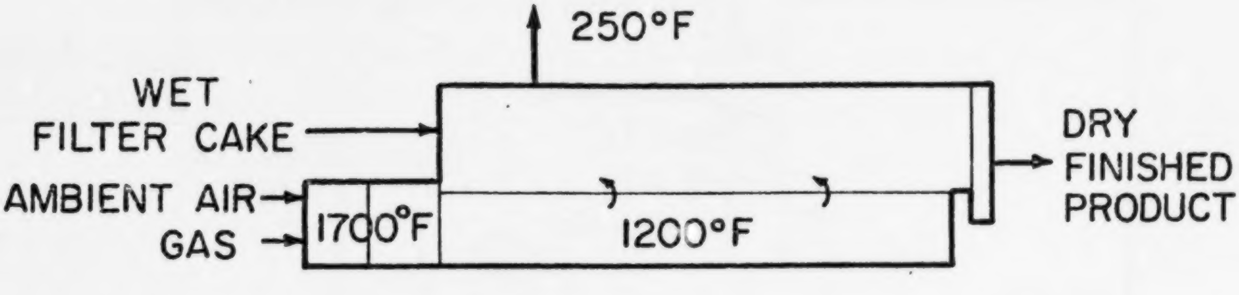
ORIGINAL PLANT ENERGY CYCLE

FUEL CONSUMPTION:

TOTAL PLANT 309.1 × 10^6 BTU/HR (HHV)

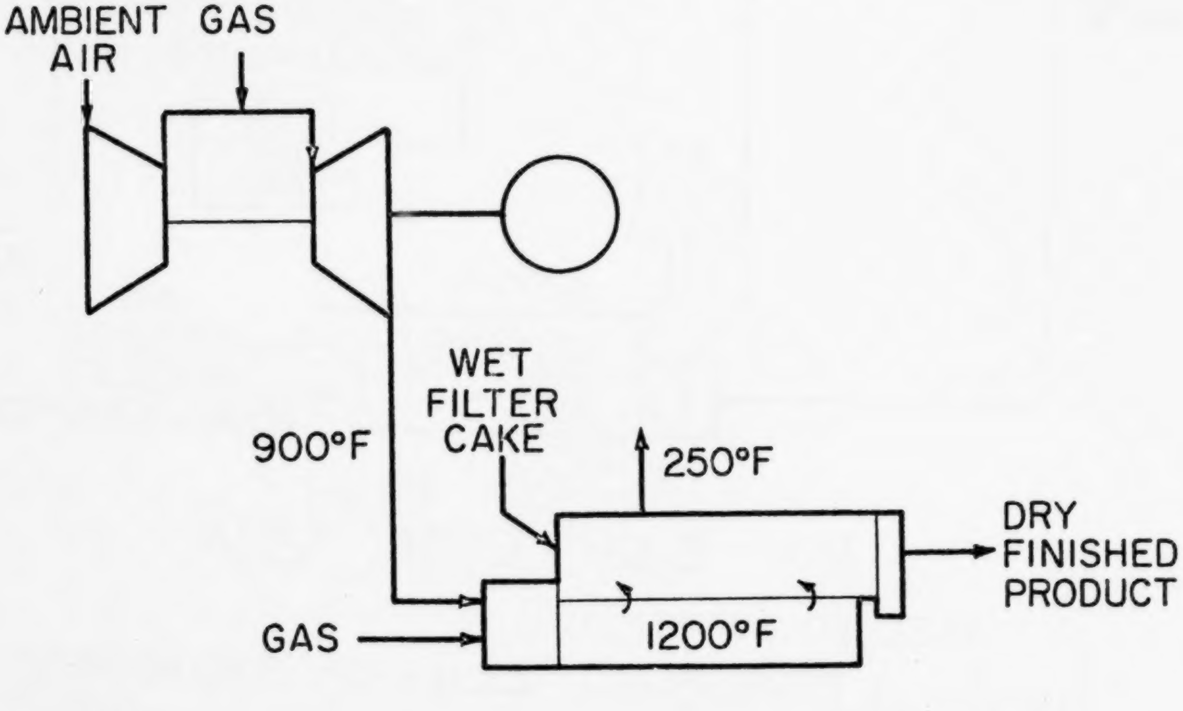
DRYER PLANT 141.6 × 10^6 BTU/HR (HHV)

FIGURE 3


250°F
WET FILTER CAKE
AMBIENT AIR
GAS
1700°F
1200°F
DRY FINISHED PRODUCT

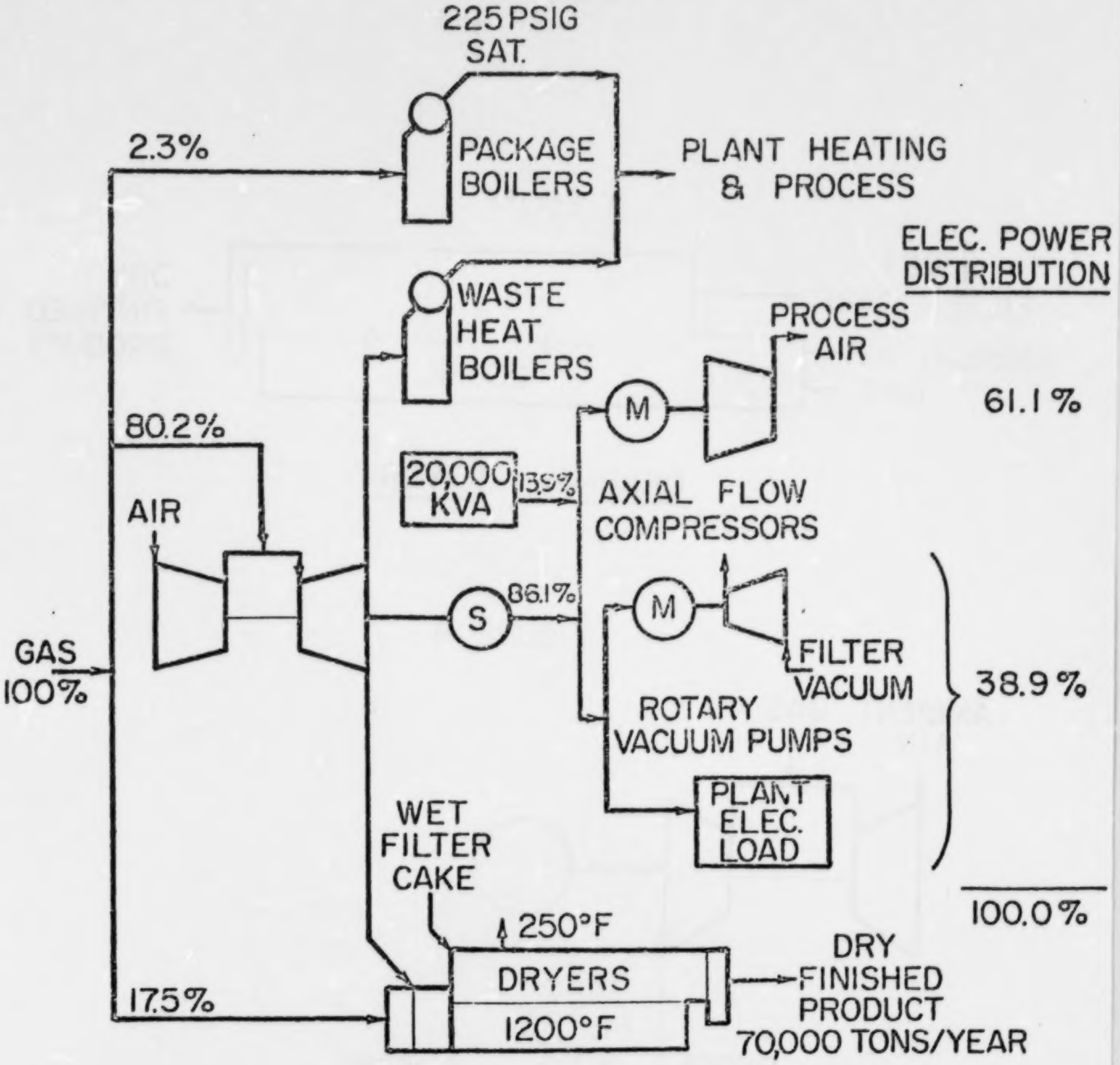
ORIGINAL DRYER

FIGURE 4


AMBIENT AIR
GAS
900°F
WET FILTER CAKE
250°F
GAS
1200°F
DRY FINISHED PRODUCT

GAS TURBINE — DRYER COMBINATION

FIGURE 5


225 PSIG
SAT.
2.3%
PACKAGE BOILERS
PLANT HEATING & PROCESS
ELEC. POWER DISTRIBUTION
WASTE HEAT BOILERS
PROCESS AIR
61.1 %
80.2%
M
20,000 KVA
13.9%
AXIAL FLOW COMPRESSORS
AIR
S
86.1%
M
FILTER VACUUM
GAS 100%
ROTARY VACUUM PUMPS
38.9 %
PLANT ELEC. LOAD
100.0 %
WET FILTER CAKE
250°F
DRYERS
DRY FINISHED PRODUCT 70,000 TONS/YEAR
17.5%
1200°F

NEW PLANT ENERGY CYCLE

FUEL CONSUMPTION:

TOTAL PLANT 232.6×10^6 BTU/HR (HHV)

DRYER PLANT 39.8×10^6 BTU/HR (HHV)

FIGURE-6

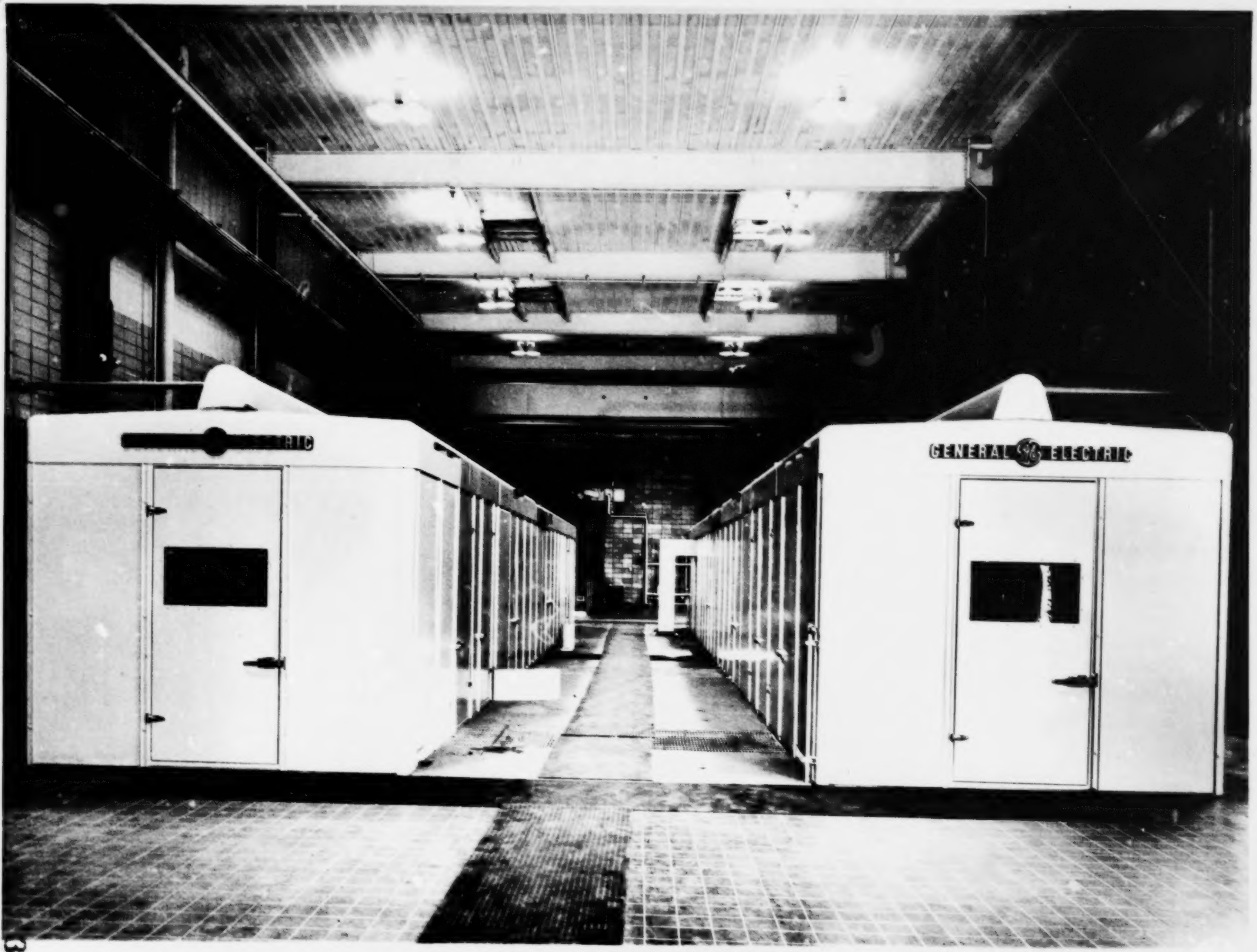

GENERAL ELECTRIC
RIC

FIGURE 7 GAS TURBINES

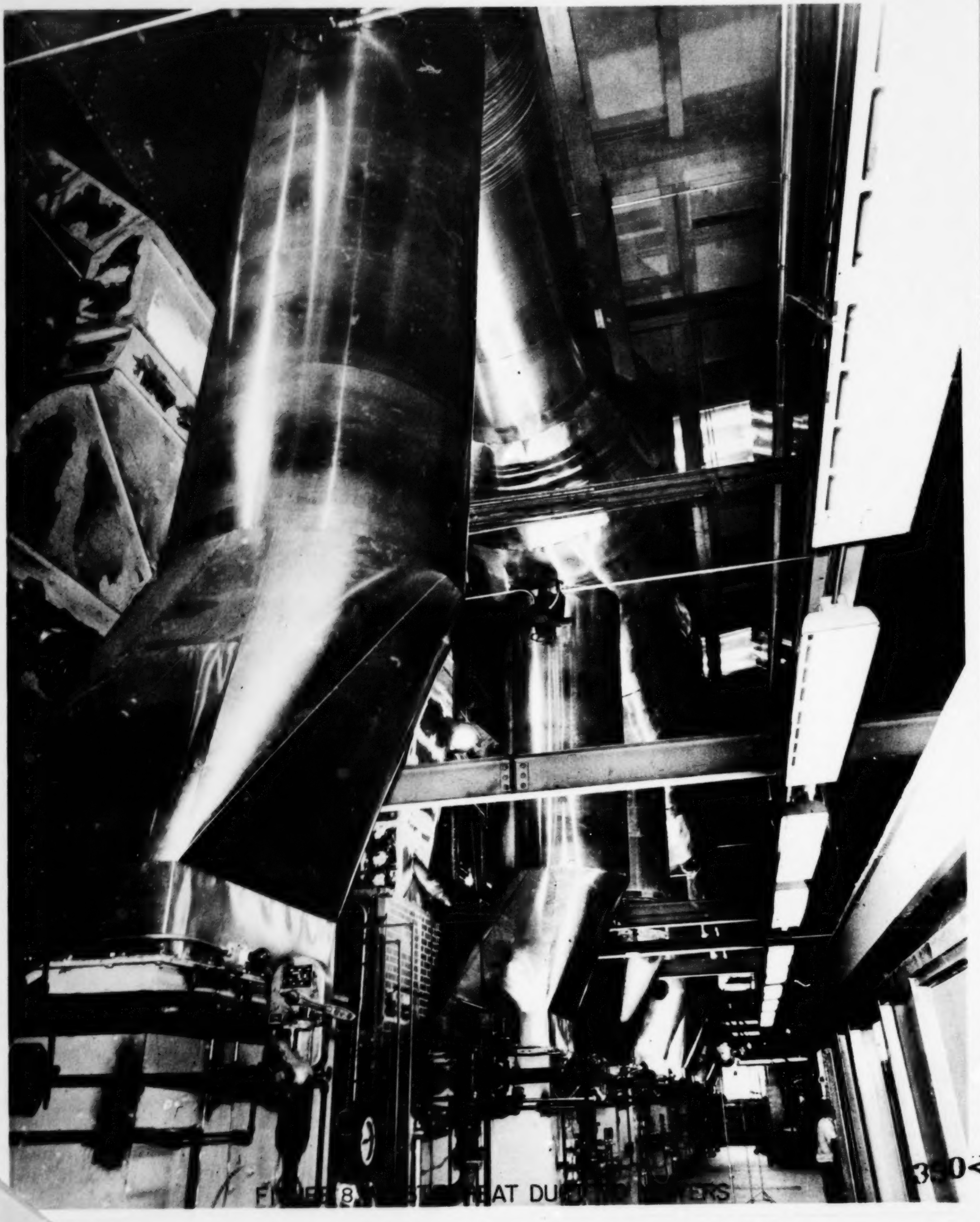
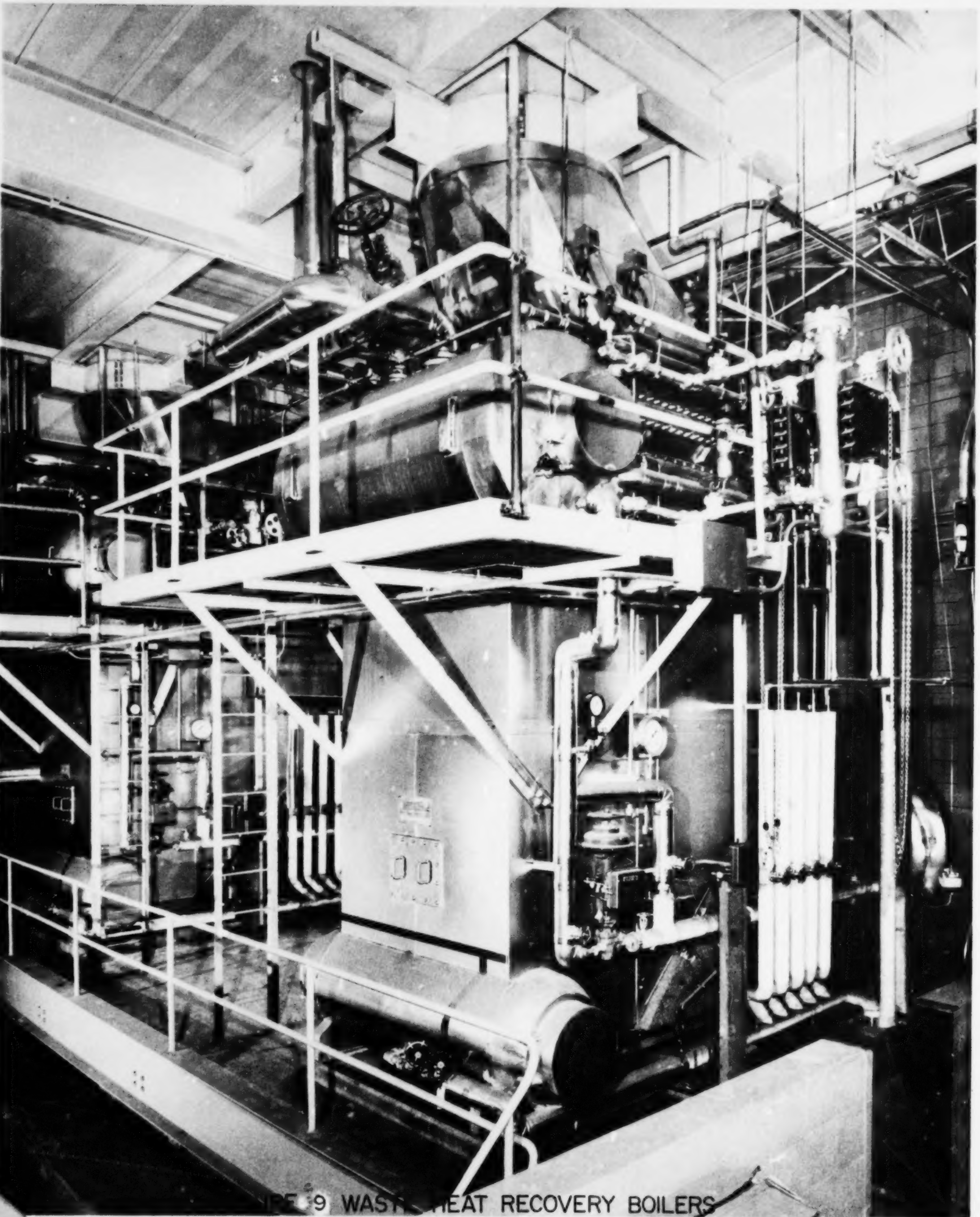


FIGURE 8. [illegible] HEAT DU[illegible] [illegible]ERS



RE 9 WASTE HEAT RECOVERY BOILERS

17-45-8

X-A-25

THERMODYNAMIC ANALYSIS OF RANKINE CYCLE ENERGY SYSTEMS UTILIZING WASTE HEAT

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ABSTRACT

Thermodynamic functions based on generalized equations of state, along with physical properties estimation methods, are demonstrated to predict with acceptable accuracy the working fluid thermodynamic properties in analyses of Rankine cycle energy systems utilizing waste heat. The analyses require a minimal knowledge of a fluid's physical properties. This generalized approach is compared with analyses using actual thermodynamic data; a High Temperature Gas-cooled Reactor Gas Turbine (HTGR-GT) binary cycle with three different bottoming cycle working fluids is examined and acceptable accuracy is attained. The method is used to predict the behavior of Refrigerant 22 as bottoming cycle working fluid. Physical properties estimation methods are used to reduce to a minimum the amount of fluid property data required as input. It is demonstrated that, when the method is used in conjunction with an optimization routine, the desirable fluid properties and cycle conditions for maximizing thermal efficiency can be determined.

INTRODUCTION

Engineering studies of Rankine cycle energy systems utilizing waste heat are often hindered by lack of good experimental data for the thermodynamic functions (enthalpy, entropy, internal energy, specific heat) and physical properties of many possible working fluids. In this paper the use of thermodynamic functions based on generalized equations of state, along with physical properties estimation methods, is proposed and demonstrated. They can be used to predict with acceptable accuracy the thermodynamic properties of a working fluid in a cycle analysis. A minimal knowledge of a fluid's physical properties is required. The objectives of this study are: to develop an analysis method, based on generalized thermodynamic state equations, to study the thermodynamic performance of Rankine power cycles and to provide a basis for cycle working fluid selection based on optimal fluid properties.

The example system used in development of the method was a bottoming power cycle to recover reject heat from the High Temperature Gas-cooled Reactor Gas Turbine (HTGR-GT) power system.[1] In the reference design HTGR-GT cycle [2,3] waste heat is rejected from the system with a dry cooling tower. If sufficient water is available for supplying a once-through cooling system or a wet cooling tower, the bottoming cycle can be used to increase the output and reduce heat rejection to the environment.

The term "secondary cycle" is used to refer to the bottoming cycle, while "primary cycle" refers to the gas turbine. "Binary cycle" will refer to the combination of the two.

BASIC SECONDARY CYCLE ANALYSIS METHOD

A schematic diagram of the system is shown in Figure 1. The working fluid as a liquid is pressurized above its critical pressure by means of a feed pump. It is then heated as a pressurized liquid, expanded through a turbine where it gives up internal energy to mechanical and electrical energy, and, finally, liquefied, in a water-cooled surface condenser where heat is rejected from the system. The fluid then enters a hotwell to repeat the cycle.

A cycle analysis requires the determination of certain fluid properties at various points in the cycle. The analysis routine used here requires the determination of the following fluid properties: vapor pressure and saturated liquid entropy and enthalpy, as functions of temperature; enthalpy as a function of entropy and pressure; temperature as a function of enthalpy and pressure; and entropy as a function of temperature and pressure. In the usual thermodynamic analysis approach extensive data tables of these properties are set up and used in conjunction with an interpolation routine to determine state properties. With this method the tables are replaced by generalized thermodynamic functions.

GENERALIZED THERMODYNAMIC FUNCTIONS FOR GASES AND LIQUIDS

Definitions

"Reduced pressure", p, is the actual pressure, P, divided by the critical pressure, P_c:

$$p = P/P_c \tag{1}$$

"Reduced density", ρ, is the critical specific volume, v_c, divided by the actual specific volume, v:

$$\rho = v_c/v \tag{2}$$

"Reduced temperature", t, is the actual absolute temperature, T, divided by the critical absolute temperature, T_c:

$$t = T/T_c \tag{3}$$

A "generalized equation of state" expresses the functional equilibrium relationship between reduced pressure, reduced density, and reduced temperature. "Generalized thermodynamic functions" are derived from generalized equations of state to predict fluid properties in a form more convenient to numerical analysis.

393<CDH

The HBMS Equation of State and Thermodynamic Functions

The Hirschfelder-Buehler-McGee-Sutton (HBMS) generalized equation of state [4,5,6] are used as the basis for the analysis. The equation gives reduced pressure as a function of reduced pressure, reduced temperature, and the following adjustable constants:

parameter β, which is uniquely related to the critical compressibility factor, z_c, by

$$z_c = \beta(3\beta-1)/(1+\beta)^3 \tag{4}$$

Riedel parameter α, which is the slope of the vapor pressure curve at the critical point:

$$\alpha \equiv dp_v/dt \quad \text{at } p_v = t = 1 \tag{5}$$

constant k_0, which is an adjustable constant used to fit the equations to known data, and

the fluid molecular weight M.

The equation of state then has the following functional form:

$$p = p(\rho, t, \beta, \alpha, k_0, M) \tag{6}$$

Enthalpy, h, and entropy, s, are functions of the same variables plus a_1, a_2,a_3,a_4, which are the coefficients in the third-order equation in temperature for ideal gas specific heat at constant pressure, c_p^o:

$$c_p^o = a_1 + a_2T + a_3T^2 + a_4T^3 \tag{7}$$

Therefore:

$$h = h(\rho, t, \beta, \alpha, k_0, M, a_1, a_2, a_3, a_4) \tag{8}$$

$$s = s(\rho, t, \beta, \alpha, k_0, M, a_1, a_2 . a_3, a_4) \tag{9}$$

For calculations for fluids in the liquid state, two auxiliary equations are needed: the Riedel equation ,[6] which gives reduced vapor pressure, p_v, as a function of reduced temperature and the Riedel parameter:

$$p_v = p_v(t, \alpha) \tag{10}$$

and the Guggenheim equation [7] for saturated liquid density, ρ_1:

$$\rho_1 = 1 + c(1-t)^{1/3} + d(1-t) \tag{11}$$

Riedel parameter α is evaluated by solving the Riedel equation for α and substituting the pressure-temperature values at the normal boiling point. For k_0, the value 5.5 recommended by Hirschfelder is used here. The coefficients a_1, a_2, a_3, a_4, are obtained from a third-order least squares fit of a table of ideal gas specific heat as a function of temperature. Constants c and d in the Guggenheim equation are determined from experimental values of saturated liquid density at two temperatures. The fluid properties required for the application of the generalized equations, then, are: the three critical constants, the molecular weight, the normal boiling point, the density of saturated liquid at two temperatures, and the coefficients of the ideal gas specific heat equation. In addition, a heat transfer coefficient for the heater must be calculated which requires knowledge of the specific heat at constant pressure, the thermal conductivity, and the viscosity.

ACCURACY OF ANALYSES USING GENERALIZED EQUATIONS

To test the accuracy of results using the generalized equations, they were compared with analyses using actual thermodynamic data. Comparisons were done for three different working fluids in the HTGR-GT bottoming cycle: isobutane, propane, and amonia. The output quantity chehed for accuracy is the secondary cycle power output. The calculated power outputs using the generalized equations all agreed to within 7% of data-input results. The comparisons demonstrate that the generalized equations can be used to predict working fluid properties with acceptable accuracy for the analysis.

APPLICATION OF THE GENERALIZED EQUATIONS

As an example of the generalized approach to a specific fluid, an analysis of an HTGR-GT binary cycle with Refrigerant 22 (chlorodifluoromethane $CHCIF_2$), R-22, as bottoming cycle working fluid was performed. Complete thermodynamic data were not available for the fluid. In Table I are shown the binary cycle efficiency and conditions necessary to achieve this efficiency for Refrigerant 22 in comparison to other working fluids. The information in Table I, which can be extended to a number of other fluids by use of the generalized equations, can be used to aid in the selection of a working fluid.

PHYSICAL PROPERTIES ESTIMATION METHODS

For many fluids a complete set of the properties required as input for analysis with the generalized equations may not be available. In these cases estimation methods can be used to predict unknown properties. The following methods were used:

for ideal gas specific heat:
The Rihani-Doraiswamy Group Contributions Method [8]

for critical properties:
The Lydersen Group Contribution Method [9]

for thermal conductivity and viscosity
The Stiel-Thodos Method [10,11,12,13,14]

The group contribution methods involve dividing up the atoms of a molecule into well-defined groups and adding up the contribution to the property of each group. The Stiel-Thodos method involves the plotting of various combinations of properties as functions of reduced density and fitting curves to the plots.

Various combinations of these estimation methods were incorporated into the generalized equations. The results were all within 16% of calculations based on actual thermodynamic data.

With these estimation methods and the generalized equation, the minimum information concerning the working fluid required can be reduced to a mere knowledge of the chemical structure and either the critical temperature or the boiling point.

MAXIMIZING THERMAL EFFICIENCY

One significant application of the generalized equations with estimation methods is that they could be used in conjunction with an optimization method to determine the desirable fluid properties and cycle conditions for maximizing thermal efficiency. The independent variables are: critical pressure, critical temperature, paramater β, molecular weight, reduced normal boiling temperature, secondary cycle maximum pressure, coefficients a_1, a_2, a_3, a_4, and the minimum helium temperature in the gas turbine cycle. An optimization analysis was applied to an HTGR-GT binary cycle with a maximum helium temperature of 1500°F and a secondary fluid condensation temperature of 90°F. The results are shown in Table II. The binary cycle efficiency shown in Table II is the best that can be expected from this cycle.

Using the properties of 70 possible working fluids and considering the sensitivity of binary cycle efficiency to each property, it was found that Refrigerant 22 closely resembles the fluid described in Table II. Indeed, this was observed (Table I). Ammonia yielded a higher efficiency but because it is a highly polar compound with an abnormally high critical pressure, it was excluded from the range of the optimization study.

It is possible that a fluid could be developed with the exact properties detailed in Table II, but the small gain in thermal efficiency makes such a development unwarranted.

Of course thermodynamic efficiency comprises only one aspect of a comprehensive fluid selection process. Further consideration of fluid characteristics such as stability, corrosiveness, flammability, cost and availibility, and toxicity must also be considered.

SUMMARY

It has been shown that cycle analyses can be done accurately using generalized equations. This is very useful when fluid selection is important as in the case of bottoming cycles which reduce waste heat rejection. The minimum information required to describe a fluid is its chemical structure and either its critical temperature or its normal boiling point. It has also been shown that optimization of the fluid properties and cycle conditions which maximize thermal efficiency can be done with the generalized approach.

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TABLE I

COMPARISON OF HTGR-GT BINARY CYCLE SECONDARY FLUIDS

Fluid	Minimum Helium Temperature in HTGR-GT Cycle	Maximum Secondary Cycle Pressure	Efficiency Calculated Using Actual Thermodynamic Data	Efficiency Calculated Using Generalized Approach
	(°F)	(psia)	(%)	(%)
Isobutane	136	1080	44.7	43.9
Propane	147	1670	42.2	42.9
Ammonia	172	2920	44.9	45.2
R-22	152	2170	-	44.6

TABLE II

RESULTS OF OPTIMIZATION

Binary Cycle Efficiency:	45.55%
Critical Pressure:	890 psia
Critical Temperature:	233 °F
Critical Density:	29 lbm/cu ft
Molecular Weight:	60
Normal Boiling Temperature:	-2.5 °F
Secondary Cycle Maximum Pressure:	1970 psia
Minimum Helium Temperature:	149 °F

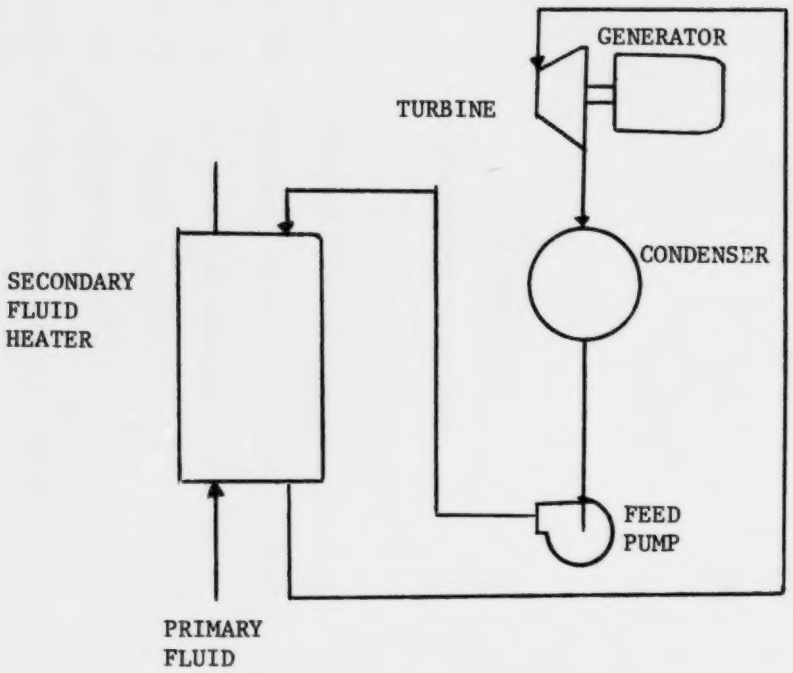
GENERATOR
TURBINE
CONDENSER
SECONDARY
FLUID
HEATER
FEED
PUMP
PRIMARY
FLUID

Fig. 1. Rankine Cycle Energy System

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POWER PLANT WASTE HEAT - DISASTER OR BOON?

ABSTRACT

With the proliferation in the numbers of Fossil and Nuclear Power Plants, tremendous amounts of waste heat are generated. Even though the current rate of energy growth is lower than in previous years, demand will continue to increase and has to be met with more power plant facilities. Are we faced with a disaster due to the continued increase in the amount of waste heat generated? Is there a potential for harnessing this for a variety of beneficial uses thereby alleviating concerns of the public, environmentalists and legislators alike? Are we in varying roles of power plant designers, consulting engineers, environmental engineers, utilities, agencies, etc. doing all we can to address ourselves in a responsible manner to the question of the sources, generation management and utilization of waste heat? In short, is waste heat looming ahead as a disaster or will it be a boon?

This paper attempts to answer the questions raised above. It looks at the energy picture ahead and estimates the growth in the numbers of Fossil and Nuclear Power Plants and the attendant waste heat. It examines effects of various parameters such as steam pressures, temperatures to improve cycle efficiencies to reduce waste heat. It examines the feasibility of using steam turbines and heat exchangers for combined power generation and district heating and how the choice of these is influenced by economic and environmental factors. It examines some of the physical aspects that involve the interrelationship between

waste heat, pollution and energy conservation. Various cooling system options, such as once-through cooling, cooling towers, spray ponds and canals are discussed and the environmental impacts of the heat released from them assessed. The roles of various agencies in regulating waste heat discharge are examined.

No magical solutions are presented but recommendations are made as to what can be done to convert the threat of waste heat assuming disastrous proportions to one of boon.

18-45-12

WASTE HEAT UTILIZATION IN AQUACULTURE: SOME FUTURISTIC AND PLAUSIBLE SCHEMES

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ABSTRACT

Futuristic and plausible aquaculture schemes for utilization of waste heat from steam generating facilities are discussed. Multiple use of land and water owned or used by a utility is the underlying theme in any of these programs.

Animals or plants that could be cultured include marine and freshwater species, such as fish, eels, shrimp, prawns, clams, seaweeds, and algae. Integration of secondarily-treated sewage effluent into these schemes for nutrient removal is also feasible. Each species envisioned for culture has commercial value such as food for humans or livestock, bait for recreational fishing, emulsifiers for industrial processes, an energy source for direct combustion, or as an energy sparing commodity. Other schemes, such as culture of marine sea turtles and manatees in thermal effluents, have benefits in conservation, weed control, and public relations programs.

INTRODUCTION

The use of waste heat from steam generating facilities for aquaculture has been well documented [1, 2]. The underlying principle of this benefit is that temperature exerts an effect on cold-blooded fish or invertebrates primarily to increase their activity and metabolism [3], which then permits a greater growth rate and a shorter rearing time. The emphasis in most of these studies has been to select food organisms (e.g. fish and crustaceans) that draw premium prices in the marketplace. However, as well accepted as this principle is, there are only two or three examples of commercial waste heat utilization by aquaculture in the United States. Japan, of course, has numerous ventures involving fish, mollusks, and shrimp [4, 5]. Numerous European countries also have examples of waste heat utilization on a commercial or pilot scale [6].

Even warm-blooded animals such as manatees, an endangered species found in southern Florida, can benefit from waste heat. During the passage of cold fronts up to 500 manatees (the entire population of Florida is approximately 1,000) are attracted to thermal effluent of several power plants [7], which have replaced "natural refugia" altered or destroyed by man [8].

Recently, interest in mass rearing of seaweeds and algae have focused on a commercial market for the product either directly as a commodity (e.g. "fuels from biomass") or as extractable "byproducts" (e.g. agar and carrageenan) [9, 10, 11]. Of additional interest and of even greater significance is the ability of seaweeds and algae to strip nutrients from water thereby achieving tertiary water treatment [12]. In these systems, heat is not as important a stimulant to the growth of aquatic plants as is flow and incident solar radiation [13].

The integration of secondarily-treated sewage effluent into a power plant cooling system has intriguing possibilities. For instance, one small municipal power plant in Florida takes secondarily-treated effluent and, with certain chemical/physical steps to prevent build-up of phosphatic scale, runs it to cooling towers as make-up water. An aquaculture system involving freshwater algae has been proposed as an alternative method of nutrient stripping.

Aquaculture of food organisms in thermal effluent either from a fossil or a nuclear unit, causes great concern to officials in several federal agencies because of possible heavy metals or radionuclide contamination and associated poisonous or carcinogenic overtones. Growth of organisms in sewage effluents, even diluted 20 fold, conjures up greater nightmares because of viral contamination. These problems are real; however, the industry can meet them head-on and solve the problems with research, can avoid them altogether by careful planning, or ameliorate them by processing and reducing contamination to harmless levels.

Multiple uses of resources and by-products can be a key conservational factor that will enhance the value and potential of aquaculture. Conservation in any form has great appeal and increasing necessity in the world of today and any effort that can integrate one resource or by-product into another process, will receive societal and/or economic benefits. Large amounts of resources are utilized in electrical production, and it is in the best interest of the industry to develop this multiple use concept. The purpose of this paper is to review some futuristic and plausible schemes in aquaculture under development or being considered by Florida Power & Light Company to develop multiple uses of its resources and by-products.

AQUACULTURE OF SEAWEEDS/FRESHWATER PLANTS

Turkey Point - Present

Surveys of biota in the 1,600 hectare saltwater cooling system at Tutkey Point reveal that approximately 15 species of macroscopic seaweeds/algae are growing in the system. There, however, appears to be a successional pattern for some species. Sea grasses such as Widgeon Grass *Ruppia*, turtle grass *Thalassia*, and shoal grass *Halodule* are presently growing throughout the year but do not have any direct commercial value. One species of red seaweed *Dasya*, which has commercial value, only proliferates in the cooler winter season and becomes vestigial during the summer. Other species of seaweeds/algae with commercial potential dominate in the summer. The succession is attributed mainly to sunlight - a summer season with intense solar radiation, and a winter season with reduced levels.

Surveys have identified a red algae *Gracilaria* present throughout southern Florida and this species has been grown under laboratory conditions in central Florida during the winter and summer [13]. *Gracilaria* production yields of circa 18-20 g dry weight/m^2/day on an annual basis are reported in Florida compared with circa 9-11 g/m^2/day for Woods Hole, Massachusetts [13]. Even though the Woods Hole facility used heated water, the yields in Florida were twice that of a northern site. Ryther et al. [13] attributed this difference to incident solar radiation between the two locations. Therefore, there is an advantage to growing seaweeds/algae in Florida.

Furthermore, Ryther et al. [13] extrapolated (with a note of caution) a mean annual yield of 20 g/m^2/day to 73 metric tons/hectare/year. This level of productivity is higher than almost any other reported yield from natural ecosystems or cultivated crops [14].

Two points discussed by Ryther et al. [13] have particular bearing on power plants. Firstly, even though water temperatures exceeded 35^{o}C in mid-summer experiments, growth of *Gracilaria* was rapid. Thus heat may not be a limiting factor for select species of plants. Secondly, turnover rates or complete water exchanges of 10-15 volumes/day with an inverse correlation of nutrient levels enhanced yields. Thus, high flow and low nutrient level stimulated yield which implied that sewage effluent (freshwater) can be greatly diluted with power plant effluent (saltwater).

Turkey Point - Future

Experiments are being planned to begin in mid-1977 to screen certain species of seaweed for growth and yield in the Turkey Point Cooling Canal System. Results will then dictate if secondarily-treated sewage can be added to the canal system for nutrient stripping by seaweeds/algae. However, since the prime function of these canals is to cool condenser water, anything that would affect plant operation (e.g. reduce flow rate, seaweed impingement) would preclude such an operation.

South Dade - Future

South Dade (a proposed site just south of Turkey Point) will contain two nuclear units (each circa 1100 MW) with large cooling towers. The make-up water for the towers will come from a series of deep brackish wells on and near the site. As a possible alternative for make-up cooling water, a proposed Metropolitan Dade Sewage Treatment Plant approximately 10 miles to the north can be tapped. Construction plans for the nuclear units will call for a series of borrow pits to be excavated on the South Dade Site and the fill will be used to elevate the units for hurricane protection. Futuristic schemes suggest that the secondarily-treated sewage (up to 3×10^5 m^3/day) can be diverted to these borrow pits, salt-tolerant seaweeds/algae can strip the nutrients (especially phosphate) from the water, and the water be cycled to the cooling towers as make-up. The seaweeds/algae used for such a clean-up may have commercial value.

Recently plans for the South Dade Site were cancelled due to economic conditions within the Company and lower projected need for electricity. However, evaluation of schemes to provide the necessary nutrient stripping are still planned.

Martin/Lake Okeechobee - Present

Florida Power & Light Company is presently constructing a 2800 hectare cooling reservoir in central Florida. Filling of this reservoir is to begin by mid-1977 and will require several years. Two oil-fired plants of approximately 750 MW each are being constructed on the site.

The source of freshwater to be used for filling this reservoir is Lake Okeechobee. Historically, Lake Okeechobee served as the headwaters of the Everglades region, but as early as 1880 major efforts were underway to drain, channelize and control water levels. These efforts increased in scope and intensity between 1900 and 1950. Today changes in the Lake's drainage basin have caused rain waters to run off farm and agricultural land rapidly, with high nutrient loads. As a result of these practices, the nutrient loads are causing eutrophication or "overfertilization" of the Lake.

Because the source of water for the cooling reservoir is Lake Okeechobee, the reservoir itself will be eutrophic. As a result of this fact, Florida Power & Light is conducting research on freshwater aquaculture systems as a means to provide nutrient stripping and a way to clean up these waters [13]. An advantage of a freshwater system is that the waste or eutrophic waters may be used directly and undiluted provided that nutrient concentrations do not exceed toxic or inhibitory levels. Research results are preliminary but indicate that a type of "polyculture" system is feasible [13]. Basically, surface floating plants (e.g. duckweed or water hyacinths) or submerged plants (e.g. *Egeria* species and *Ceratophyllum*) are growing in ponds stocked with herbivores such as grass carp (*Ctenopharyngodon*) or the Malaysian prawn (*Macrobrachium*). The plants function as nutrient strippers and excess yields are grazed upon by the animals.

Martin/Lake Okeechobee - Future

If a freshwater aquaculture system proves to be beneficial at nutrient removal, then a futuristic scheme of operation would be to convert the cooling reservoir to a semi-closed or even a once-through system. A massive aquaculture system could strip the nutrients from the water before or after passage through the plant, the "scrubbed" water could be discharged back to Lake Okeechobee and cooler but nutrient-laden water taken from the Lake at another point. Economic and efficiency considerations in a plant operation are directly related to the intake water temperature (e.g. the cooler the water the more efficient the operation). Thus, there may be a trade-off that can be advanced to federal and state agencies whereby the Company removes nutrients from the water and trades "clean but thermally polluted water" for "eutrophic but cooler water."

Vero Beach - Present

The municipality of Vero Beach has a power plant with a total output of approximately 105 MW. The newest unit of approximately 45 MW is of particular interest because it is on a closed-cycle cooling system. Water circulates between the condensers and the cooling tower with make-up water being derived from the adjoining municipal sewage treatment plant. In order to minimize build-up of scale in the cooling tower, phosphate levels of the secondarily-treated sewage effluent must be reduced by chemical/physical means. Cooling tower blowdown is discharged into a nearby estuary.

Vero Beach - Future

Florida Power & Light Company, in conjunction with Dr. John Ryther of Woods Hole Oceanographic Institution and Harbor Branch Foundation, Fort Pierce, Florida, has developed on a conceptual basis plans to tap the hot side of the cooling tower blowdown water to supply an aquaculture system. These plans are feasible because Florida Power & Light was in the process of purchasing the power plant from the town of Vero Beach. However, the sale of the plant is tied up in litigation requiring a revamping of conceptual plans.

In the latest pilot-scale plans, waste heat is not a prime factor, but could be added in at a later time. Basically, the concept is to divert seawater from the intake canal, dilute it with secondarily-treated sewage and run it into a circular racetrack for nutrient stripping by seaweeds. A similar system mixing drinking water and sewage would be used for nutrient removal by freshwater algae. If nutrient stripping from the freshwater system is successful, the clean water could be diverted to the cooling towers making chemical/physical means of nutrient stripping unnecessary.

The objective of these experiments is to take seaweed culture in Florida (a state with an abundance of incident solar radiation) a step beyond laboratory experiments and advance it to pilot-scale size. The Company is preparing a formal proposal to ERDA detailing these plans and requesting matching funds.

AQUACULTURE OF REPTILES, FISH AND INVERTEBRATES

Turkey Point - Present/Past

Green turtles, a marine species, are presently being held in a pen enclosure for several purposes: determining the feasibility of rearing an endangered species in thermal effluent; enhancing their conservation; and testing the ability of the turtles to control the growth of a prolific aquatic grass.

Green turtles need to be conserved because man has been destroying or modifying their traditional breeding grounds - isolated beaches along the Florida coast. The turtle has also been extensively hunted for its meat and calipe, an ingredient in turtle soup. The State of Florida has initiated a "head start" program whereby green turtle eggs are gathered from nests, incubated until hatching, reared until the hatchlings reach approximately 6 months of age, and subsequently released to the ocean. This is believed to be a beneficial program because predation on the small hatchlings is intense during the first six months. If the turtles are grown to this age or even older prior to release, then as the reasoning continues, this should constitute a conservational program.

Because turtles are cold-blooded, their growth rate is dependent upon water temperature. Additionally, green turtles are generally carnivorous during the first year of life (jellyfish are the preferred food) and switch to a herbivorous mode of feeding thereafter.

Turkey Point has numerous canals suitable for turtle pens. The system has heated water to enhance their growth. Because jellyfish grow naturally in the system and are abundant, the turtle hatchlings have more than enough to eat. Post one-year old turtles will eat a seagrass *Ruppia* that grows naturally in the system. This seagrass grows so well that it is becoming a major problem for plant operation because it is retarding the flow of seawater in the system and must be controlled. The turtles, therefore, may act as a limited method of biological control.

The Malaysian prawn *Macrobrachium rosenbergii* is also being raised in experimental and pilot-scale facilities at Turkey Point. This work is being conducted at the same site formerly leased by the University of Miami.

Many people believe that the climate of south Florida is nearly ideal for the culture of *Macrobrachium*. However, experience over the last several years has shown that, even in Miami, natural bodies of water drop below optimum temperature for the species (28-29°C). Thus, for a year-round operation, supplemental heating must be provided for approximately 3-4 months of the year.

Florida Power & Light is conducting this R&D program in conjunction with Farm Fresh Shrimp Corporation of Fort Lauderdale, Florida, and has just initiated this work. Farm Fresh has developed proprietary technology for intensive culture of shrimp utilizing a closed system. The temperature of the system can be optimized with heat exchangers.

Because the adult shrimp are basically a freshwater species, with only saltwater requirement for breeding, they may be cultured at a number of freshwater sites with supplemental heat being drawn from existing cooling reservoirs when necessary. Thus, thermal aquaculture is most promising for this species.

Smith [15] attempted to raise pompano in floating cages at Turkey Point. He met with limited success citing inadequate diet, poor water quality, excessive fouling of cages as reasons for rearing difficulties. Nevertheless, he demonstrated that cage culture was feasible, but did not continue the project.

Tabb and Yang [16] also described culture work with penaeid shrimp at Turkey Point. However, they were never able to raise these shrimp in quantities large enough and on a sustained basis for any commercial venture. Problems with water quality, shrimp biology, and federal regulations prevented a continuation of this work.

Turkey Point - Future

Because two nuclear units draw cooling water from the Turkey Point cooling canals, federal regulations prevent organisms grown in contact with tritiated water from being used for human consumption. However, shrimp grown for the bait industry may be exempted.

The saltwater bait shrimp industry is an extremely lucrative business, with fishermen paying up to five cents per three-inch live shrimp. Florida Power & Light is contemplating growing saltwater shrimp in the Turkey Point cooling canals for bait.

Manatees or sea cows, an endangered species, are another organism that may be propagated in the Turkey Point cooling canals for conservational purposes. Boats and, perhaps, cold weather are the major mortality factors for this species. Food, warmth, and shelter are abundant in the canal system, but federal regulations pertaining to endangered species may not allow such introductions.

Sanford - Past

The Sanford reservoir was completed in 1971 and subsequently an independent contractor began the cage rearing of catfish. The objective was to enhance catfish growth with heated effluent. The project was abandoned a year later when the cages broke up and the catfish escaped into the reservoir.

Martin/Manatee/DeSoto - Future

Recently, personnel of the Florida Game & Fresh Water Fish Commission made a scientific breakthrough in the artificial spawning of the very popular sport fish - the snook. This fish attains weights of up to 15 kg, has a prestigious reputation as being a "fighting fish," and can live equally well in freshwater and saltwater habitats. The snook's distribution is limited by water temperature and snook kills are very common in cold weather.

Florida Power & Light has freshwater reservoirs at Manatee (presently in operation) and Martin (under construction) that are at the northern limits of the snook's distributional range. The thermal effluent discharged into these reservoirs would be ideal to help the snook "overwinter" when they ordinarily would not. Stocking of these reservoirs with fingerling snook would create a fisherman's paradise; and, because the fish are a voracious carnivore, they would help to check the population numbers of trash fish in the reservoirs. Because snook are "game" fish by Florida Statutes, they cannot be sold, but Florida Power & Light can certainly sell the right to catch them on its private land. Thus, a "fee" fishing business could be set up along major tourist routes.

Waste heat can also be integrated into a cattle feed lot operation. One operation, Kaplan Industries located in Bartow, Florida, operates on a "closed-loop" cycle. The system operates in the following manner: solid and liquid wastes from up to 20,000 head of cattle are collected by an automated system from a 7.5 hectare area; the wastes are washed and processed to separate fibrous solids and liquids; the solids are treated and go back, as roughage, into the cattle's feed; the remaining liquids flow to a series of lagoons where they are first treated anaerobically and then aerobically; the water, which is high in nutrients, flows to a final lagoon where it stimulates a dense algal bloom; the algae are cropped by herbivorous fish which are either sold or fed back to the cattle; the water in the fish lagoon which has been stripped of nutrients is used for cattle drinking water and irrigation of feed crops.

The anaerobic digestion step is where waste heat may be integrated into the process. The optimum temperature for this fermentation is 40°C, which presents problems during the winter in Florida. However, by locating a cattle feed lot adjacent to a cooling reservoir, heat exchangers can maintain this anaerobic process at an optimum temperature. Interestingly, methane is a by-product of this step which could be diverted to the power plant for combustion. Another by-product, carbon dioxide, can be converted into dry ice.

The freshwater prawn Macrobrachium can be used for bait as well as food. However, because this prawn is an exotic or "non-native" species in Florida, present State regulations require that the shrimp be dead prior to sale. Nevertheless, the market for frozen bait shrimp is good. This could be one of several programs if a nuclear unit were located on a freshwater reservoir, such as Florida Power & Light's proposed reservoir at the DeSoto Site.

Japan presently cultures a freshwater clam for pearls and shells that are made into buttons. A culturing enterprise such as this could also be set up in a freshwater reservoir, cooling one or more nuclear units. Artificial pearls and buttons obtained would not be subjected to as much governmental regulation as products grown for food.

Japan also cultures tremendous volumes of eels, which are considered a delicacy. Again, freshwater cooling reservoirs, with or without nuclear units, would be an ideal place to culture this organism and the meat could be marketed abroad. The State of North Carolina, with funds from Sea Grant, has set up eel culturing facilities and the prospect of aquaculture for this species looks promising [17].

CONCLUSIONS

Aquaculture as an economic enterprise has a double edge as many industries and people learned to their chagrin in the 1960's. Because many fish or invertebrates can be propagated on a laboratory/research scale, they reasoned that a commercial venture was reasonably and profitably near. Many culturing unknowns existed at that time (e.g. disease, nutrition, water quality) and when profits were not forthcoming, many withdrew their investments.

Today, there is a feeling of cautious optimism in the field of aquaculture. However, only several aquaculture firms in the continental United States made a profit in 1976 with many more declaring bankruptcy. So, there is still a long and difficult task ahead, integrating waste heat and flow into aquaculture systems. The ideals and concepts expressed are certainly intriguing possibilities for multiple uses of by-products. Whether some of these schemes border on the realm of "fantasy" or whether there are indeed merits to such ideas will remain to be seen.

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Session X B

In-Situ Data Acquisition

19-45-21

X-B-49

SUBMERGED MULTIPORT DIFFUSER THERMAL DISCHARGES FROM CONCEPTUAL DESIGN TO POSTOPERATIONAL SURVEY

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ABSTRACT

This paper summarizes the design concept and thermal predictions for the James A. FitzPatrick Plant diffuser prior to the construction as well as the methodology and results of a series of postoperational thermal plume mapping.

Preoperational lake surveys were performed to provide detailed hydrographical data for conducting and evaluating the hydraulic model and analytical studies. Near-field and far-field thermal plumes were predicted by the laboratory and mathematical models for various lake current conditions.

Three postoperational hydrothermal surveys were conducted in June, August, and October, 1976. Three-dimensional thermal patterns are documented for ranges of ambient temperatures, current speeds and directions, and stratified and unstratified lake conditions. In addition, the diffuser performance in terms of dilution factors was given by dye concentrations existing in the lake after releasing dye into the circulating water system. These field surveys represent the first comprehensive performance test of a major multiport thermal diffuser.

Predicted and observed thermal plumes are compared, while dye concentration information is used to gain better understanding of the mixing mechanism and performance of the diffuser jets with respect to the natural lake thermal stratification and lake currents.

INTRODUCTION

The James A. FitzPatrick Nuclear Power Plant, utilizing a submerged multiport diffuser once through cooling discharge system, has been in commercial operation since July 1975. The 850 MWe plant is located on the south side of Lake Ontario near Oswego, New York.

The plant withdraws a maximum of 825 cfs from Lake Ontario for plant cooling. Flow from an intake tunnel under the lake bottom enters a free surface screen well from which three vertical shaft centrifugal pumps withdraw 785 cfs, and circulate it through the main condenser to produce a 32.4° F temperature rise at full load. In addition, a maximum of 40 cfs is withdrawn for service water requirements, which will produce a 13.5° F rise in temperature. A total of 825 cfs will therefore be discharged, with a maximum temperature rise of 31.5° F at the offshore points of discharge after flowing from a free surface well through a tunnel under the lake bottom. The heat rejection rate in the condenser is 5.714×10^9 Btu/hr.

The concept of intake and discharge structures is to produce thermal patterns which would comply with the New York State thermal discharge criteria prevailing at the time of design. The design criteria were the natural surface ambient water temperature, which should not be raised more than 3° F except within a radius of 300 ft or equivalent area from the point of discharge, and the thermal discharges should be confined to the epilimnetic area.

DESIGN CONCEPT AND ENVIRONMENTAL STUDIES

The basic concept of the discharge structure consists of multiple submerged ports forming a diffuser. Sufficiently high initial jet velocities and relative submergence below the water surface produce rapid dilution of the condenser cooling water by entraining large quantities of colder ambient lake water. The characteristics of the diluted surface flow layer formed after the initial jet entrainment zone will be such that the intake will be in a region void of warm water and thus provide assurance that no recirculation will occur.

To provide a sound basis for developing and predicting the effect of the plant cooling water discharge, field surveys were conducted to measure lake temperatures and lake currents. Data obtained from these surveys were used in analytic and hydraulic model studies to develop the hydraulic design of the structures and to ensure that the temperature patterns to be produced by plant operation would comply with the thermal discharge criteria of the State of New York.

The following is a list of the environmental studies which lead to the final design of the plant cooling water circulating system:

A. Field Studies

1. Continuous recording of currents and temperatures at various depths for six months from late spring to fall.
2. Two overall lake current pattern surveys using drogues.
3. Two overall surface temperature pattern surveys using airborne infrared radiometry.
4. Four temperature profiles in deep water by traversing with single thermistor.

B. Meteorological Studies

Collection of wind speed and direction data from four weather stations and the adjacent Nine Mile Point Station anemometer to correlate with lake currents.

C. Hydraulic Model Studies

1. Basic study of submerged jet dilution to determine characteristics of surface layer (1/26 scale).

2. Lake model. To select optimum orientation and direction of discharge (1/50 vertical, 1/200 horizontal scales).

3. Details of discharge structure. Selection of design characteristics of discharge nozzles (1/50 scale).

4. Complete discharge and intake model. Location and design of intake; temperature patterns with lake currents (1/81 scale).

D. Analytic Studies

1. Develop basic concept and design features of structures.

2. Predict overall hydrothermal patterns of cooling water discharge.

STUDY RESULTS AND ADOPTED DESIGN

Lake Conditions

Lake current and temperature measurements provided detailed information on the physical lake environment at the James A. FitzPatrick site. Lake currents at the site are primarily wind induced and low in magnitude, usually only a few tenths of a foot per second. The currents generally follow the lake topography. Temperatures of the lake water vary according to atmospheric conditions. The thermocline exists at 40 to 50 ft below the surface in deep water during late summer. The lake structures are in the epilimnion during times of stratification. In the vicinity of the lake structures, significant natural upwellings have been recorded, with colder hypolimnetic water replacing epilimnetic water. [1], [2]

Hydraulic Model Tests and Final Design

The extensive hydraulic model testing program, in conjunction with analytic studies, was used to develop the hydraulic design of the intake and discharge structures. A submerged diffuser structure discharging high velocity jets which produce rapid decrease in condenser cooling water temperature was selected as the final discharge structure of the power plant. The design of the diffuser was complicated by the fact that the direction of the warm surface flow has to be determined in order to locate an intake in a region unaffected by the warm water. Also, the existence of the Nine Mile Point Power Plant 3200 ft to the west was a factor, since the cumulative effects of both plants had to be considered. The most desirable scheme turned out to be a single line of submerged jets essentially parallel to the shore with the jets discharging horizontally toward the lake. A total of 12 jets are discharged in pairs from six diffuser heads at an initial velocity of 14 fps at 5 to 6 ft above lake bottom. The direction of the discharge is lakeward and essentially perpendicular to the bottom contours. Fig. 1 shows the arrangement of intake and discharge system and Fig. 2 depicts the discharge structure diffuser head.

For all lake current conditions, i,e., no current, eastward and westward, currents ranged from 0.2 fps to 0.8 fps, the model test results showed the surface water temperature would not be raised more than 3° F outside the permissible zone. It was also shown that the concept and location of the intake structure are satisfactory. No recirculation of warm water was detected with or without lake currents. Basic results from the model tests of the flow pattern and temperature distribution along a section perpendicular to the shoreline through the James A. FitzPatrick lake structures are shown on Fig. 3.

A more detailed description of the field study and hydraulic model test programs with the adopted design of intake and discharge structures can be found elsewhere.[3]

Far-Field Thermal Plume Prediction

Because of physical size limitations which precluded determining the overall site temperature patterns from the hydraulic models, the overall thermal patterns at the site were predicted analytically using the hydrothermal conditions determined from the model tests in the vicinity of the discharge structure. Analytic solutions of heat dispersion from the discharge were obtained for the condition of a static lake and for the condition of lake currents of different speeds.

For a static lake, analytic solutions for the discharge plume were obtained by analogy to a hypothetical surface jet. This hypothetical jet is defined such that it simulates the velocity and temperature distribution found in the model approximately 300 ft downstream from the diffuser structure. The predicted temperature pattern is shown in Fig. 4. It is evident that a symmetrical plume is formed lakeward of the diffuser, with a relatively rapid drop in temperature due to dispersion.

To analyze overall temperature patterns with lake currents, it was necessary to establish the center line of the discharge plume. The cooling water discharge is deflected in the direction of the prevailing current as the velocity of the jets decreases. Using the entire flow field as a single jet, available data on deflection of jets in moving environments were used to establish the flow center line. Lateral spread of the flow field along the center line was computed by considering the dispersion of a continuous line source. Fig. 5 shows the predicted temperature patterns for eastward current of 0.2 fps. In general, low current speeds produce a broader plume with less total area within the 0.5° F temperature rise isotherm than is the case for high currents. Analyses of heat loss to the atmosphere indicate only a small decrease in plume temperature at any point.

The above-described analytical methods have been compiled by Argonne National Laboratory in the report "State-of-the-Art of Analytical Modeling."[4]

POSTOPERATIONAL HYDROTHERMAL SURVEYS

A program of hydrothermal field surveys were undertaken for the James A. FitzPatrick plant to determine the three-dimensional thermal patterns produced by the joint operation of a nearby 600 MWe station and the FitzPatrick plant. In addition the program was to determine the diffuser performance of the James A. FitzPatrick plant based on dye concentrations existing in the lake after releasing dye into the FitzPatrick plant circulating water system.

In 1976, extensive three-dimensional thermal and dye patterns were obtained in June, August, and October. The diffuser discharge plume was documented by on-boat temperature and dye measurements while traveling along established transects. The survey boat was specially equipped with a boat mounted fixture to record temperatures at 1, 2, 6, 10, and 15 ft and dye concentrations at 1, 6, and 10 ft simultaneously. A 20% solution of Rhodamine WT dye was injected into the plant's circulating water system at a rate of 7.5 pounds per hour. Injection of the dye upstream of the circulating water pumps assured that the dye was fully mixed prior to leaving the diffuser. Background fluorescence was determined before dye release was begun to allow for correction of all dye concentrations measured during the survey. A minimum of 12 hours of dye release was allowed for the establishment of steady state conditions in the lake.

The nearfield study area consisted of a system of transects marked by buoys and spaced typically 200 ft apart. In addition, a farfield study area was established to document the extent of the thermal plume in the flow-away zone and the interaction with the thermal plume of the nearby 600 MWe power plant. Figure 6 shows the location of the transects defining the nearfield and farfield study areas.

In addition to the measurements made along the transects, temperature and dye concentrations were obtained at 27 vertical profiling stations. An in situ tower, located 2,000 feet east of the centerline of the diffuser and 1,000 feet offshore, continuously recorded lake current speed and direction, lake temperature, and lake level during the survey period.

Aquatec, Incorporated of South Burlington, Vermont was contracted to carry out the field work. A total of 22 resolutions of the thermal plumes and dye concentrations in the FitzPatrick discharge area were obtained during 1976. The time span required for each plume resolution was generally limited to one and a half hours with one boat utilized for horizontal transects and two boats for vertical profiling. Five resolutions per day were attempted, however, weather conditions occasionally limited the number of resolutions taken in a day.

The survey results have been grouped into typical plume configurations which represent the plume behavior under various sets of lake conditions. Lake conditions considered of importance in effecting the behavior of the thermal plume are ambient temperature, lake current, lake level, and the amount of thermal stratification.

Plant Operating Conditions

During the hydrothermal surveys of 1976 the James A. FitzPatrick plant was operating at loads ranging between 85 and 93 percent of its rated megawatt capacity. The June and August surveys were conducted at plant loads of 780 and 790 megawatt, respectively. The plant load during the October survey was at 725 megawatt. The average temperature rise across the plant was approximately 29° F for the June and August survey and 26° F for the October survey.

June Survey

At this time of year, Lake Ontario exhibits a warming trend with weak thermal stratification. During the survey period, the lake surface temperatures fluctuate between 47° F and 62° F while the currents are variable in magnitude from both easterly and westerly directions at the study area.

On June 4 and 13, 1976, 6 different plume resolutions were obtained. Each near-field plume resolution consisted of 6 temperature maps and 3 dye concentration maps. One map each of temperature and dye concentration were obtained for the far-field study area. In the near-field study area, the 6 temperature maps consist of isotherms in increments of 1° F for 1-, 2-, 6-, 10-, and 15- ft depths and the surface temperature rise above ambient. The three dye concentration maps consist of isopleths in parts per billion for 2-, 6-, and 10- ft depths. Both temperature and dye concentration maps for the far-field study area are measured at 1.5 ft from the water surface.

In addition to the above, 27 vertical temperature and dye concentration profiles are documented over the study areas. The horizontal transect and vertical information yields the complete 3-dimensional plume characteristic prevailing at the time of measurement.

Fig. 6 represents the temperature rise above ambient at the water surface (1 ft depth) for June 13, 1976. This run was considered to be representative of the weak stratified lake condition with an insignificant lake current. Dye contours at the 2 ft depth taken for the same period of time as the thermal measurements are shown on Fig. 7.

Temperature rise observed at the water surface were less than 2° F within an area equivalent to a 300 ft radius circle for all six measurements. This illustrates that in respect to the surface temperature rise, the diffuser during the weak thermal stratified lake condition performs at a thermal efficiency better than that assumed for design.

The plant cooling water is well mixed with the ambient lake water, forming a uniform thermal plume thickness of approximate 20 ft directed offshore from the diffuser. The well defined dye plumes truely represent the configuration of the heated plume discharged from the diffuser. No dye concentration was found in the intake structure and near shore areas.

August Survey

The lake experienced moderate thermal stratification during the two-day survey on August 19 and 20, 1976. Temperature differences between surface and bottom waters were up to 6° F in the study area with average natural surface water temperatures of 69° F and 71° F for August 19 and 20, respectively. A total of 10 different plume resolutions, 5 per day, were obtained.

Fig. 8 represents the near-field surface plume map for a moderate stratified lake condition with an average westward current at 0.20 fps. The warmer surface water overlying the diffuser is noticeably cooled by the surfacing of the thermal plume. Fig. 9 demonstrates that the boundary of the thermal plume as marked by dye coincides with the region in which surface cooling is observed.

The presence of lower surface water temperatures at the diffuser discharge area was caused by entrainment of large quantities of cool bottom water into the discharge jets and efficient mixing with warmer surface water. There was no noticeable warm surface plume formed during the survey period. As evidenced in the June survey, the dye plumes also exhibited a well defined configuration in respect to the plume thickness, concentration level contour, and plume boundary. Except for one near-field plume resolution and scattered small areas, all of the dye concentration maps indicated a dilution factor of more than 10 was achieved in the near-field rapid mixing.

The effect of a submerged diffuser discharge on the overlying warmer surface water is further demonstrated in the far-field temperature measurements as shown on Fig. 10. The nearby Nine Mile Point Station discharge created a relatively thin warm surface layer at the J. A. FitzPatrick site area. The diffuser discharge essentially lowered the temperature of the near-field surface water and increased the temperature of a limited area in the far-field for no more than 1° F, by pushing the surface isotherms further toward the direction of the diffuser discharge. Very insignificant dye concentrations were detected in the intake water shaft.

October Survey

The third survey of 1976 was conducted on October 7 and 8. The wind direction was generally from the west and northwest during daylight hours of October 7, 1976. The wind direction changed overnight and by the time of October 8 daylight hours, the prevailing wind direction was from the northeast and north. At the study area, the lake also experienced changing in current directions from eastward during October 7 to the westward during October 8, 1976. The current speeds on October 7 were 0.4 fps in the morning and diminished to insignificant magnitudes in the afternoon. During the afternoon of October 8, the lake currents were fairly steady toward the west with speeds of about 0.5 fps.

Weak thermal stratification was observed on the first day of the survey with approximate 2° F temperature difference between the surface and bottom waters. However, during the afternoon of October 8, thermal stratification was absent due to substantial mixing by strong onshore winds and waves. The average natural surface water temperature was 60.5° F during the survey period.

Total of 6 different plume resolutions were obtained: two near-field and two far-field plume resolutions on October 7, and only one resolution for both the near-field and far-field plumes on October 8 due to the rough lake conditions.

Fig. 11 and 12 represent the surface temperature rise above ambient and dye concentration contours, respectively for the homogeneous lake condition with a westward current at 0.5 fps. It is interesting to note that dye concentration patterns correlate well with temperature patterns for this homogeneous lake condition.

DISCUSSION

A combination of field studies, hydraulic model tests, and analytical studies led to the final design of the cooling water intake and discharge structures for the James A. FitzPatrick Nuclear Plant. A good understanding of the hydrographic characteristics of the receiving water body and the behavior of diffuser discharges proved to be essential for the final design. Based on the extensive postoperational surveys conducted during 1976, the design of submerged diffuser and intake structures are adequate and have functioned as expected with minimum impact on the environment.

Four surveys were planned for 1976 to document the submerged diffuser discharge plume resulting from the operation of the James A. FitzPatrick plant under all possible lake conditions. Due to severe lake conditions during the winter season, the scheduled survey in December was canceled. As a result, three surveys were conducted for the months of June, August and October. However, during the survey periods the lake experienced wide range of variations in respect to temperature, current and thermal stratification. The parameters considered important for the purpose of measuring the thermal plume are those of lake temperature, current speed and direction, lake thermal stratification, lake level, onshore and offshore winds, nearby Nine Mile Point Station discharge, and plant operating conditions. The surveys were conducted for the plant operating continuously at loads greater than 80%.

Inclusion of the dye tracer measurement program in the survey scope of work has provided very important information, such as, the interaction of the FitzPatrick plume and the Nine Mile Point plume, the configuration of diffuser discharge plume, and the mechanisms of diffuser performance. The interaction of two nearby cooling water discharges can be easily and clearly assessed by evaluating the temperature and dye concentration maps. Under thermal stratified lake conditions, temperature distributions of the thermal plume are not well defined because of the low temperature rise of the plume and large variation of the natural water temperatures. Injection of dye into the cooling water system and complete mixing with the discharge water provided a display of the well defined plume in respect to the horizontal boundary extents, plume thickness, and the mixing behavior of jets under all lake conditions.

Since the hydraulic model tests and analyses were performed for homogeneous lake conditions, meaningful comparison of the predicted and field measured temperatures should be based on the same homogeneous density conditions. Therefore, with dye concentration information, the actual diffuser performance for each condition can be evaluated to assess the accuracy of predicted results.

The survey results clearly indicated that the diluted surface warm layer, formed after the initial jet rapid mixing, was directed toward offshore and thus avoid recirculation through the intake structure. During a majority of all survey periods there was no recirculation, however, for several short periods of time dye was detected in the intake water shaft representing an insignificant amount of temperature rise, less than 1° F.

ACKNOWLEDGMENT

The James A. FitzPatrick Nuclear Power Plant is owned by the Power Authority of the State of New York, which sponsored all the studies that led to the final design and the postoperational field surveys.

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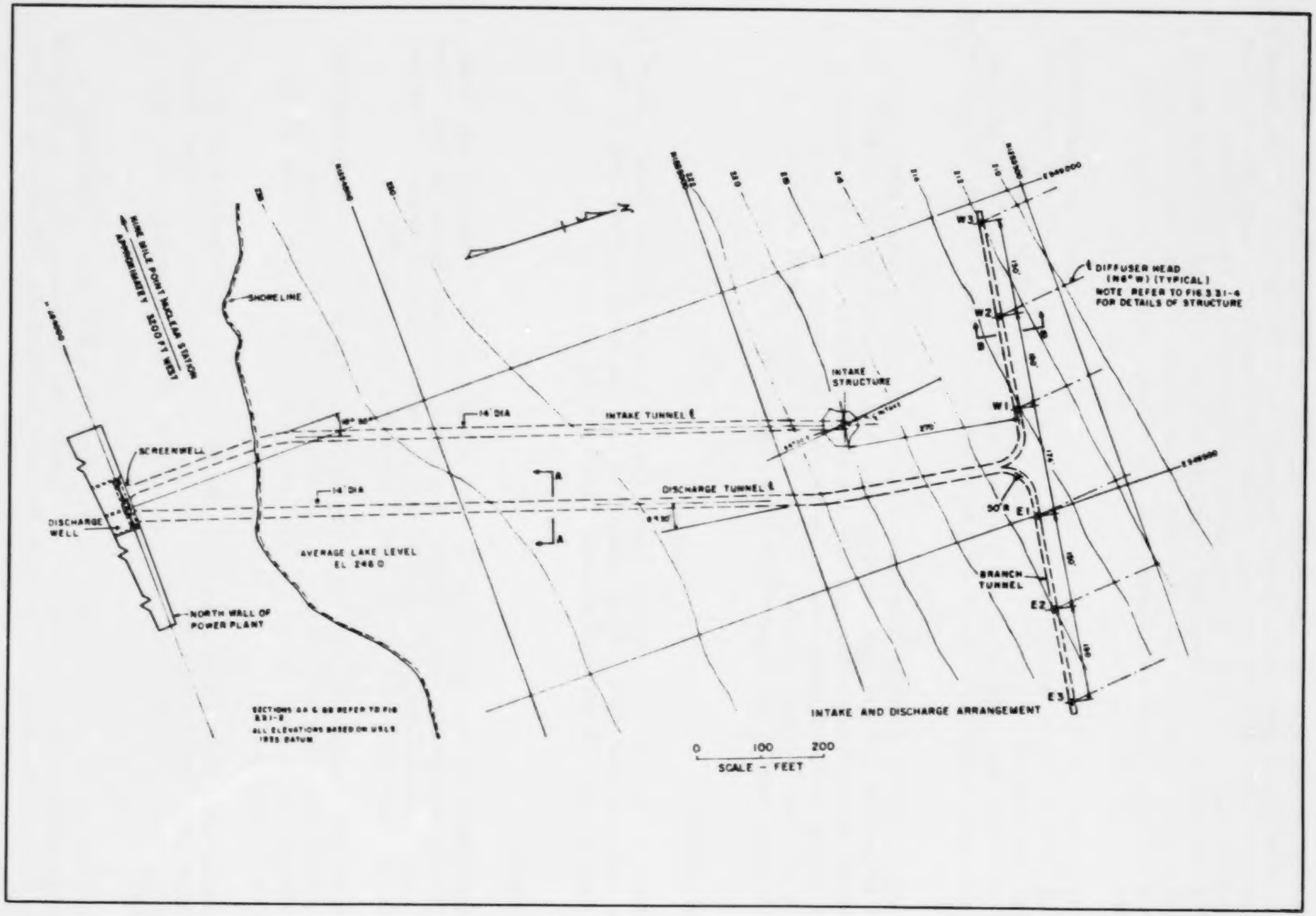

NINE MILE POINT NUCLEAR STATION
APPROXIMATELY 3200 FT WEST
N
SHORELINE
SCREENWELL
DISCHARGE WELL
NORTH WALL OF POWER PLANT
AVERAGE LAKE LEVEL
EL 246.0
14' DIA
14' DIA
INTAKE TUNNEL ℄
DISCHARGE TUNNEL ℄
A
A
INTAKE STRUCTURE
W3
W2
W1
E1
E2
E3
B
B
150'
180'
174'
180'
150'
270'
90'R
BRANCH TUNNEL
℄ DIFFUSER HEAD (N6°W) (TYPICAL)
NOTE REFER TO FIG 3.3.1-4 FOR DETAILS OF STRUCTURE
SECTIONS AA & BB REFER TO FIG 3.3.1-2
ALL ELEVATIONS BASED ON USLS 1935 DATUM
INTAKE AND DISCHARGE ARRANGEMENT
0
100
200
SCALE - FEET

Figure 1. Intake and Discharge Arrangement

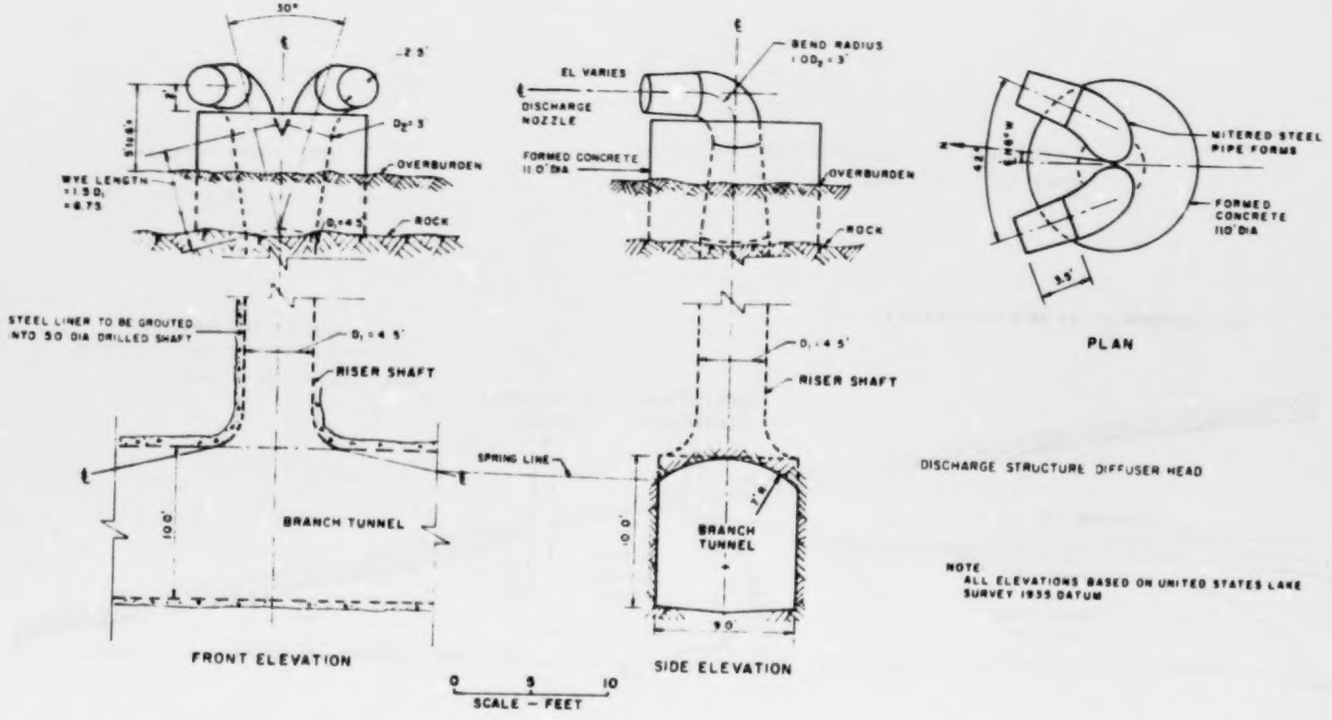

30°
2.5'
5'
5'(±6")
$D_2 = 3'$
WYE LENGTH
= 1.5 D_1
= 6.75
OVERBURDEN
ROCK
$D_1 = 4.5'$
STEEL LINER TO BE GROUTED
INTO 5.0 DIA DRILLED SHAFT
$D_1 = 4.5'$
RISER SHAFT
SPRING LINE
BRANCH TUNNEL
10.0'
FRONT ELEVATION
0
5
10
SCALE – FEET
BEND RADIUS
1.0D_2 = 3'
EL VARIES
DISCHARGE
NOZZLE
FORMED CONCRETE
11.0' DIA
OVERBURDEN
ROCK
$D_1 = 4.5'$
RISER SHAFT
2.8'
BRANCH
TUNNEL
10.0'
9.0'
SIDE ELEVATION
N
4.2'
6.0" R
MITERED STEEL
PIPE FORMS
FORMED
CONCRETE
11.0' DIA
3.5'
PLAN
DISCHARGE STRUCTURE DIFFUSER HEAD
NOTE
ALL ELEVATIONS BASED ON UNITED STATES LAKE
SURVEY 1935 DATUM

Figure 2. Discharge Structure Diffuser Head

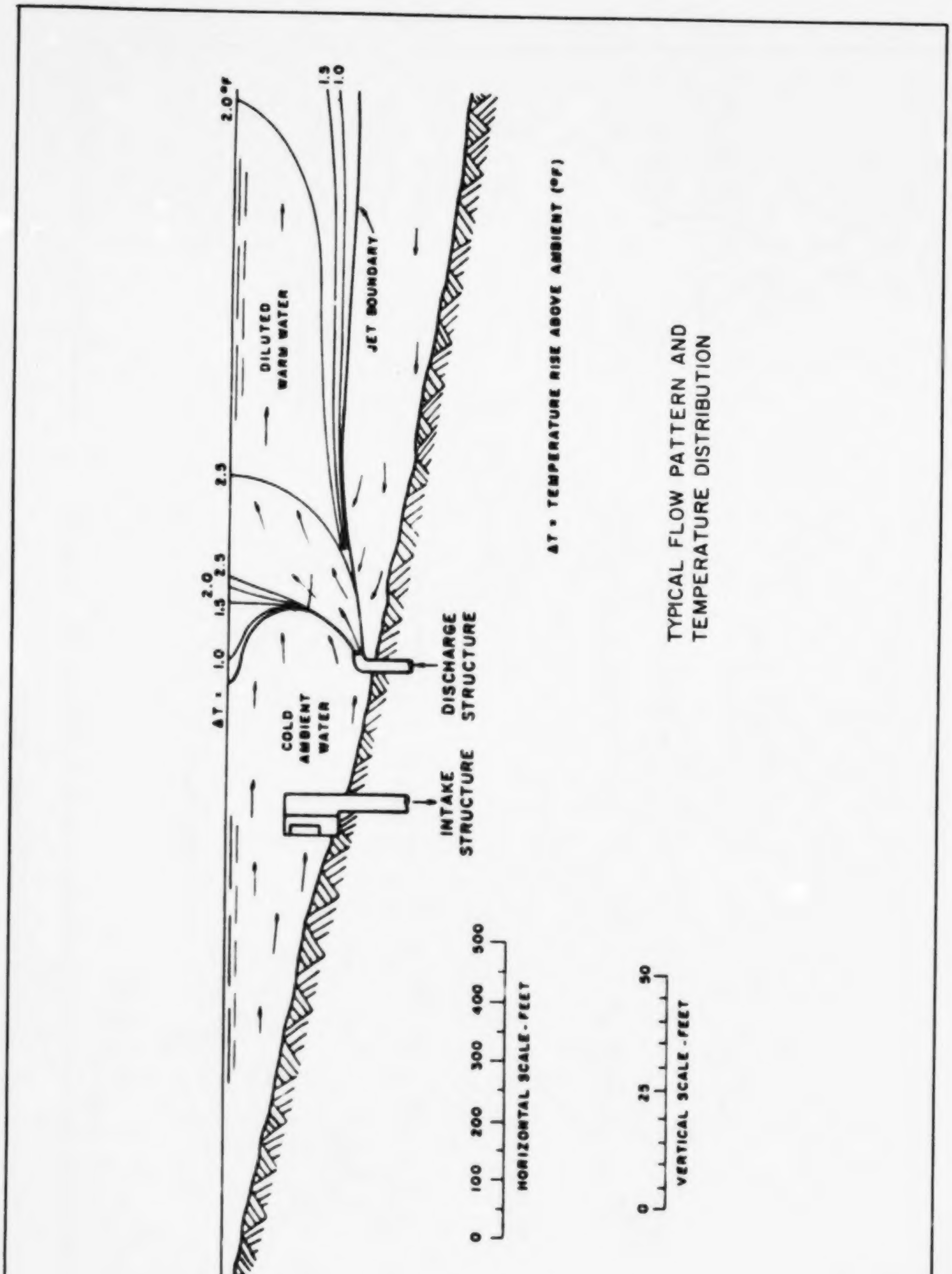

ΔT = 1.0
1.5
2.0
2.5
2.3
2.0°F
1.5
1.0
COLD AMBIENT WATER
DILUTED WARM WATER
JET BOUNDARY
INTAKE STRUCTURE
DISCHARGE STRUCTURE
ΔT = TEMPERATURE RISE ABOVE AMBIENT (°F)
TYPICAL FLOW PATTERN AND TEMPERATURE DISTRIBUTION
0
100
200
300
400
500
HORIZONTAL SCALE - FEET
0
25
50
VERTICAL SCALE - FEET

Figure 3. Typical Flow Pattern and Temperature Distribution

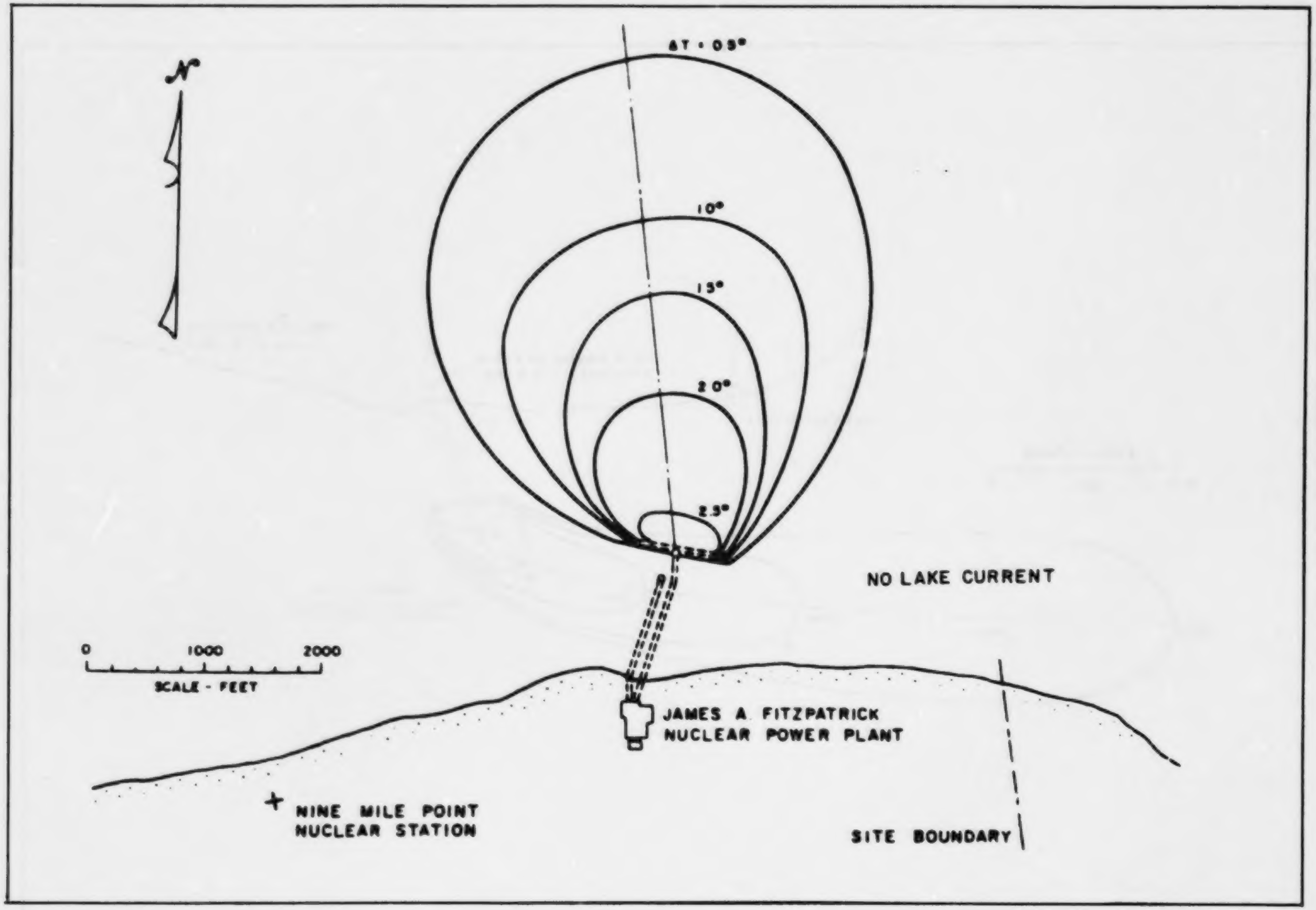

N
ΔT = 0.5°
1.0°
1.5°
2.0°
2.5°
NO LAKE CURRENT
0
1000
2000
SCALE - FEET
JAMES A. FITZPATRICK
NUCLEAR POWER PLANT
NINE MILE POINT
NUCLEAR STATION
SITE BOUNDARY

Figure 4. Predicted Surface Temperature Patterns - No Current

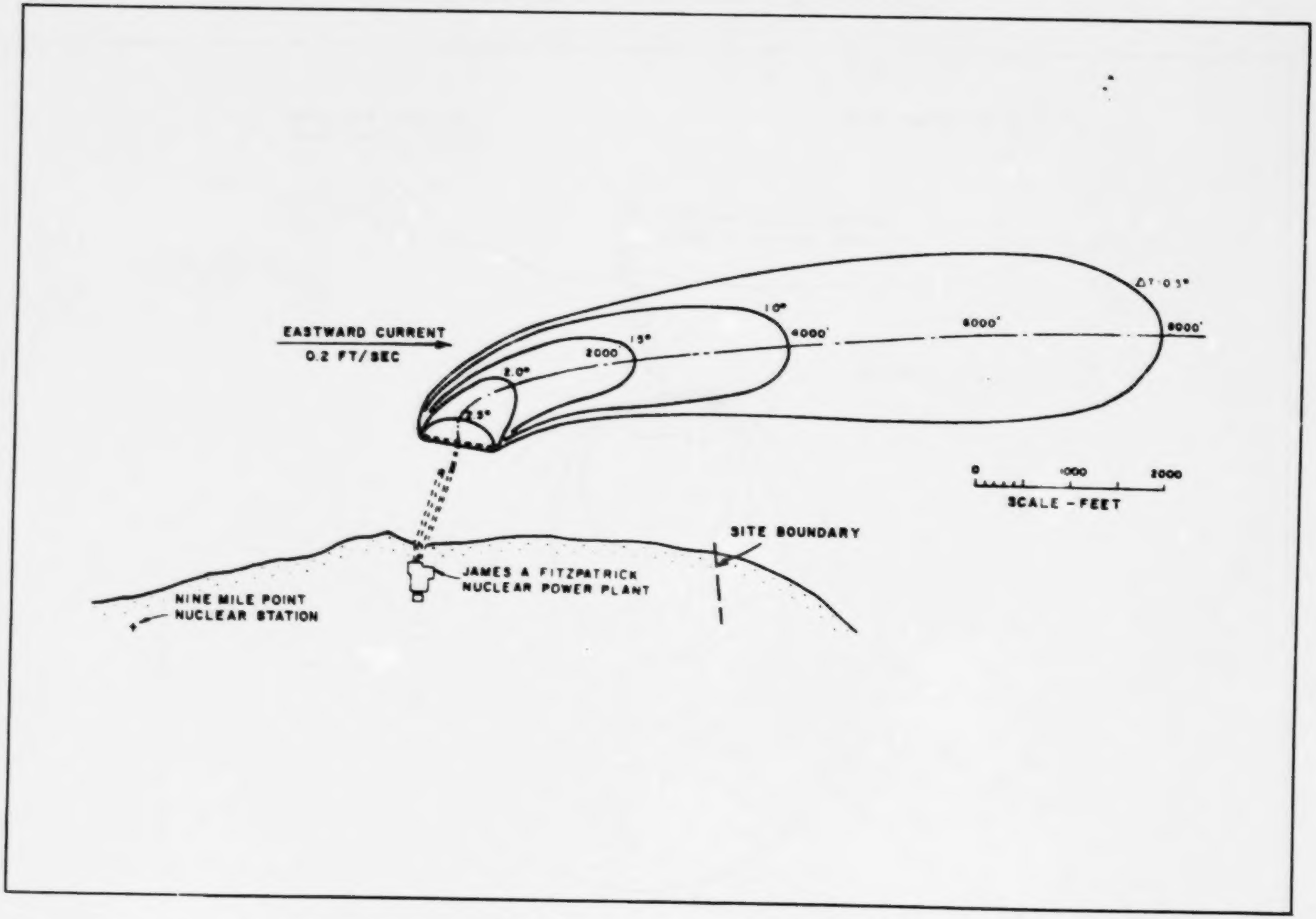

EASTWARD CURRENT
0.2 FT/SEC
ΔT·0.3°
1.0°
1.5°
2.0°
3°
2000'
4000'
6000'
8000'
0
1000
2000
SCALE - FEET
SITE BOUNDARY
JAMES A FITZPATRICK
NUCLEAR POWER PLANT
NINE MILE POINT
NUCLEAR STATION

Figure 5. Predicted Surface Temperature Patterns - With Current

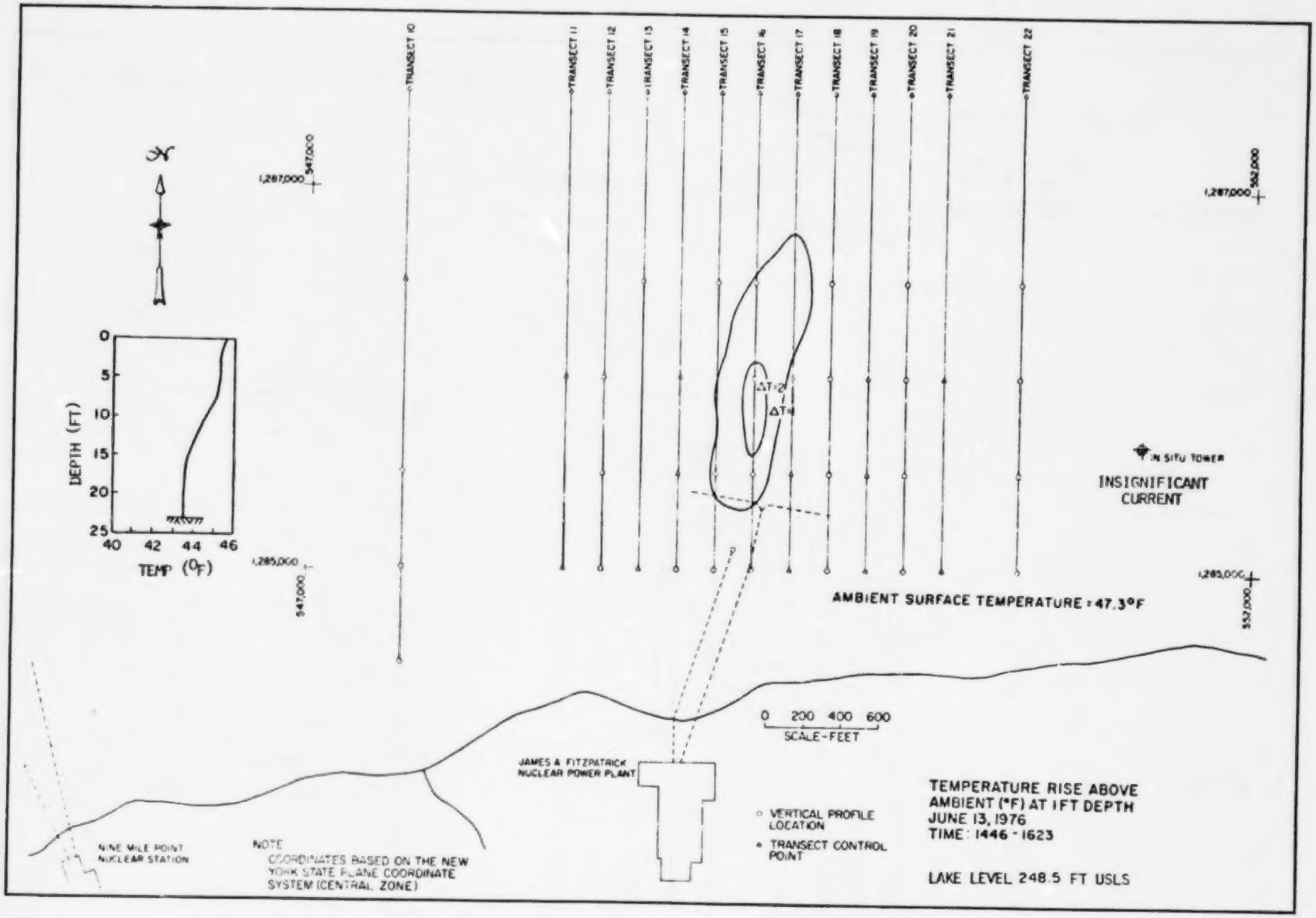
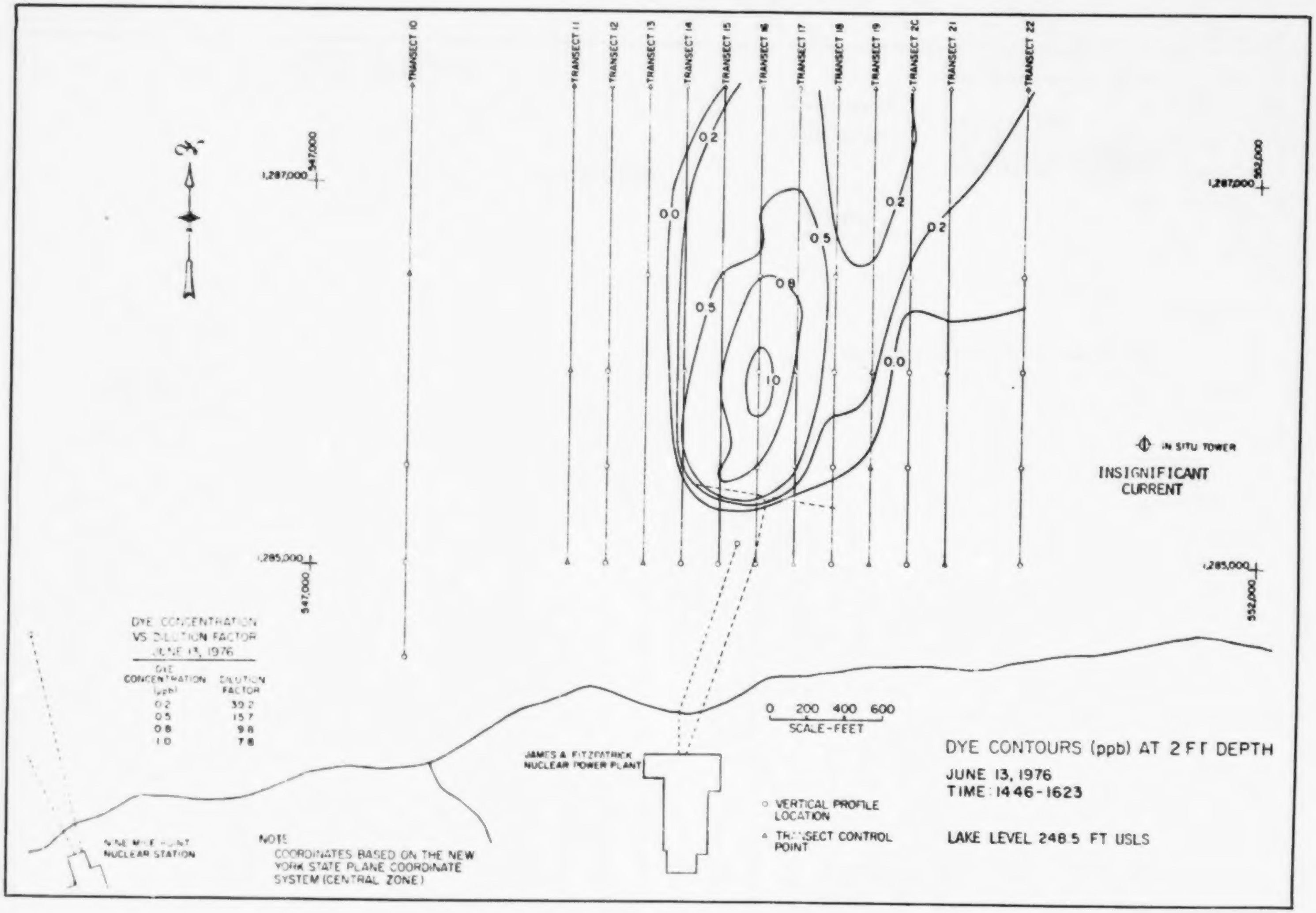

TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
1,287,000 547,000
1,285,000 547,000
1,287,000 552,000
1,285,000 552,000
N
DEPTH (FT)
0
5
10
15
20
25
40
42
44
46
TEMP (°F)
ΔT=2
ΔT=4
IN SITU TOWER
INSIGNIFICANT CURRENT
AMBIENT SURFACE TEMPERATURE = 47.3°F
0 200 400 600
SCALE-FEET
JAMES A. FITZPATRICK NUCLEAR POWER PLANT
○ VERTICAL PROFILE LOCATION
• TRANSECT CONTROL POINT
TEMPERATURE RISE ABOVE AMBIENT (°F) AT 1 FT DEPTH
JUNE 13, 1976
TIME: 1446 - 1623
LAKE LEVEL 248.5 FT USLS
NINE MILE POINT NUCLEAR STATION
NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)

Figure 6. Weak Stratified Lake Condition - Temperature


TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
1,287,000 547,000
1,285,000 547,000
1,287,000 552,000
1,285,000 552,000
0.0
0.2
0.5
0.8
1.0
IN SITU TOWER
INSIGNIFICANT CURRENT
0 200 400 600
SCALE-FEET
JAMES A. FITZPATRICK NUCLEAR POWER PLANT
NINE MILE POINT NUCLEAR STATION
VERTICAL PROFILE LOCATION
TRANSECT CONTROL POINT

DYE CONTOURS (ppb) AT 2 FT DEPTH

JUNE 13, 1976
TIME: 1446-1623

LAKE LEVEL 248.5 FT USLS

DYE CONCENTRATION
VS DILUTION FACTOR
JUNE 13, 1976

DYE CONCENTRATION (ppb)	DILUTION FACTOR
0.2	39.2
0.5	15.7
0.8	9.8
1.0	7.8

NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)

Figure 7. Weak Stratified Lake Condition - Dye

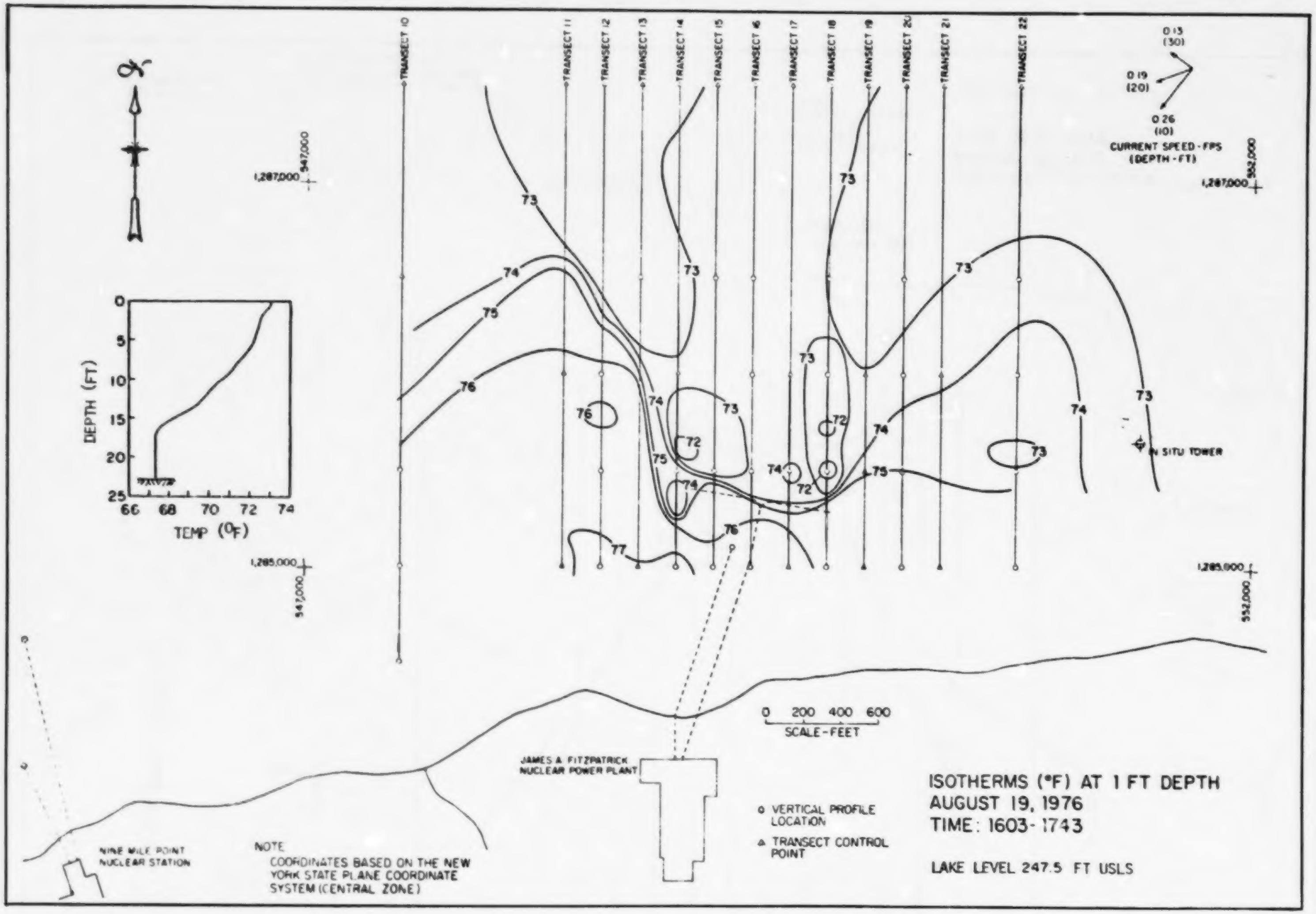

TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
0.13 (30)
0.19 (20)
0.26 (10)
CURRENT SPEED - FPS (DEPTH - FT)
1,287,000
547,000
552,000
1,285,000
DEPTH (FT)
0
5
10
15
20
25
66
68
70
72
74
TEMP (°F)
73
74
75
76
77
72
IN SITU TOWER
JAMES A. FITZPATRICK NUCLEAR POWER PLANT
NINE MILE POINT NUCLEAR STATION
0 200 400 600
SCALE-FEET
o VERTICAL PROFILE LOCATION
▵ TRANSECT CONTROL POINT
ISOTHERMS (°F) AT 1 FT DEPTH
AUGUST 19, 1976
TIME: 1603-1743
LAKE LEVEL 247.5 FT USLS
NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)

Figure 8. Moderate Stratified Lake Condition - Temperature

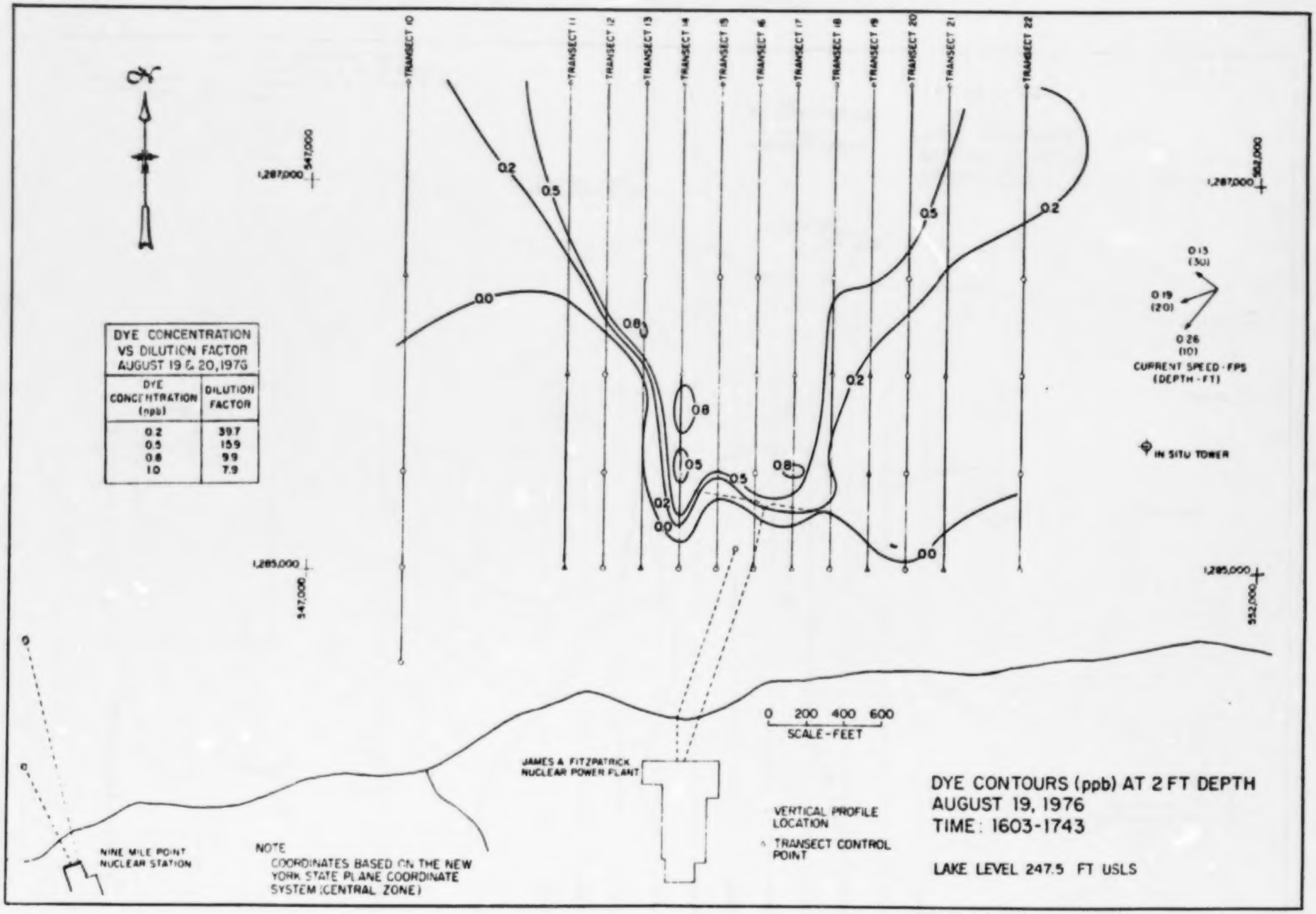

DYE CONCENTRATION VS DILUTION FACTOR AUGUST 19 & 20, 1976
DYE CONCENTRATION (ppb)
DILUTION FACTOR
0.2 39.7
0.5 15.9
0.8 9.9
1.0 7.9
1,287,000
547,000
1,285,000
547,000
TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
0.2
0.5
0.0
0.8
0.8
0.5
0.5
0.8
0.2
0.0
0.2
0.5
0.0
0.2
1,287,000
552,000
0.13
(30)
0.19
(20)
0.26
(10)
CURRENT SPEED - FPS
(DEPTH - FT)
IN SITU TOWER
1,285,000
552,000
0 200 400 600
SCALE - FEET
JAMES A. FITZPATRICK NUCLEAR POWER PLANT
NINE MILE POINT NUCLEAR STATION
NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)
VERTICAL PROFILE LOCATION
TRANSECT CONTROL POINT
DYE CONTOURS (ppb) AT 2 FT DEPTH
AUGUST 19, 1976
TIME: 1603-1743
LAKE LEVEL 247.5 FT USLS

Figure 9. Moderate Stratified Lake Condition - Dye

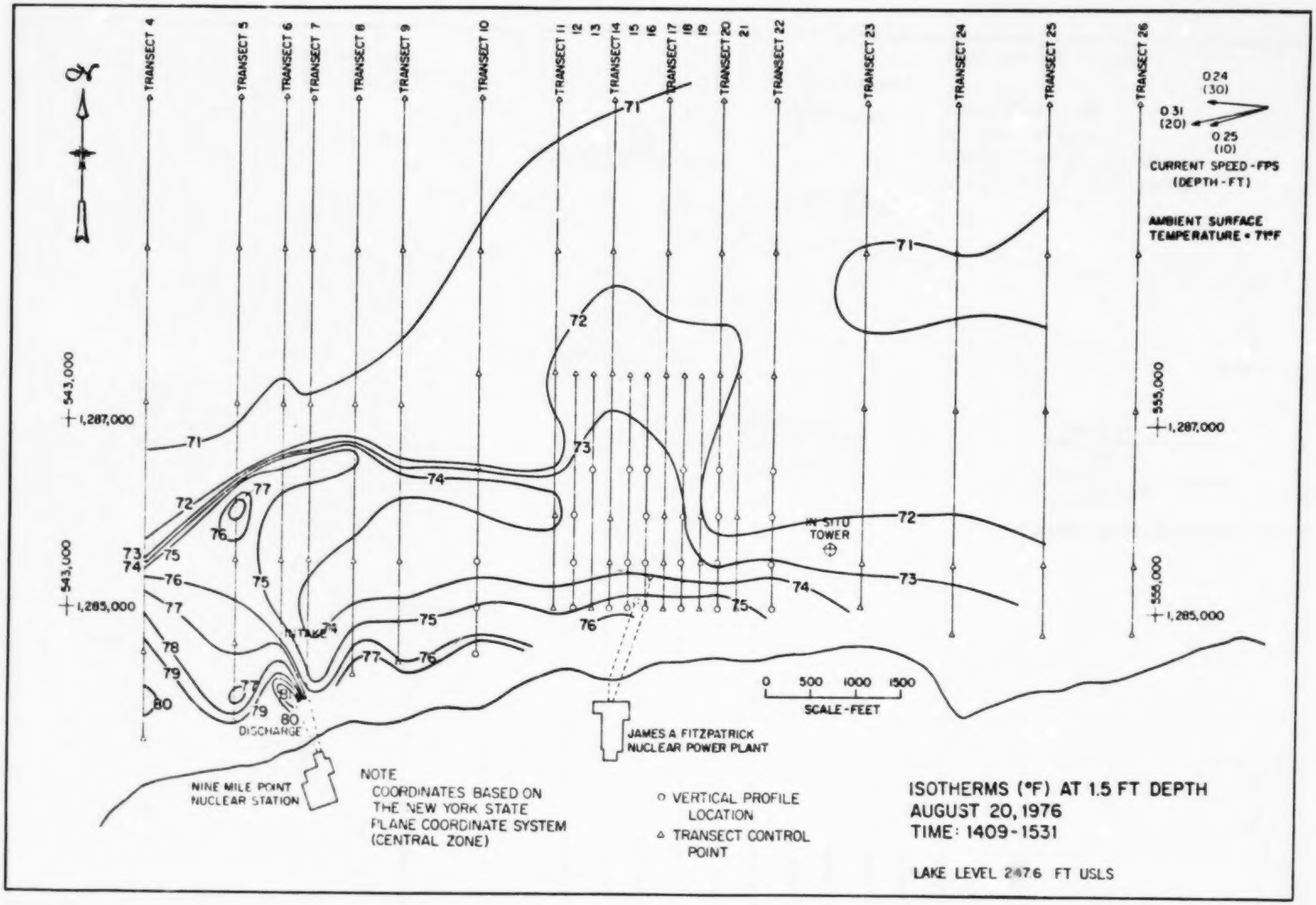

TRANSECT 4
TRANSECT 5
TRANSECT 6
TRANSECT 7
TRANSECT 8
TRANSECT 9
TRANSECT 10
TRANSECT 11
12
13
TRANSECT 14
15
16
TRANSECT 17
18
19
TRANSECT 20
21
TRANSECT 22
TRANSECT 23
TRANSECT 24
TRANSECT 25
TRANSECT 26
0.24
(30)
0.31
(20)
0.25
(10)
CURRENT SPEED - FPS
(DEPTH - FT)
AMBIENT SURFACE
TEMPERATURE = 71°F
543,000
1,287,000
543,000
1,285,000
555,000
1,287,000
555,000
1,285,000
71
72
73
74
75
76
77
78
79
80
INTAKE
DISCHARGE
IN SITU
TOWER
0
500
1000
1500
SCALE - FEET
JAMES A FITZPATRICK
NUCLEAR POWER PLANT
NINE MILE POINT
NUCLEAR STATION
NOTE
COORDINATES BASED ON
THE NEW YORK STATE
PLANE COORDINATE SYSTEM
(CENTRAL ZONE)
○ VERTICAL PROFILE
LOCATION
△ TRANSECT CONTROL
POINT
ISOTHERMS (°F) AT 1.5 FT DEPTH
AUGUST 20, 1976
TIME: 1409-1531
LAKE LEVEL 247.6 FT USLS

Figure 10. Farfield Surface Temperature

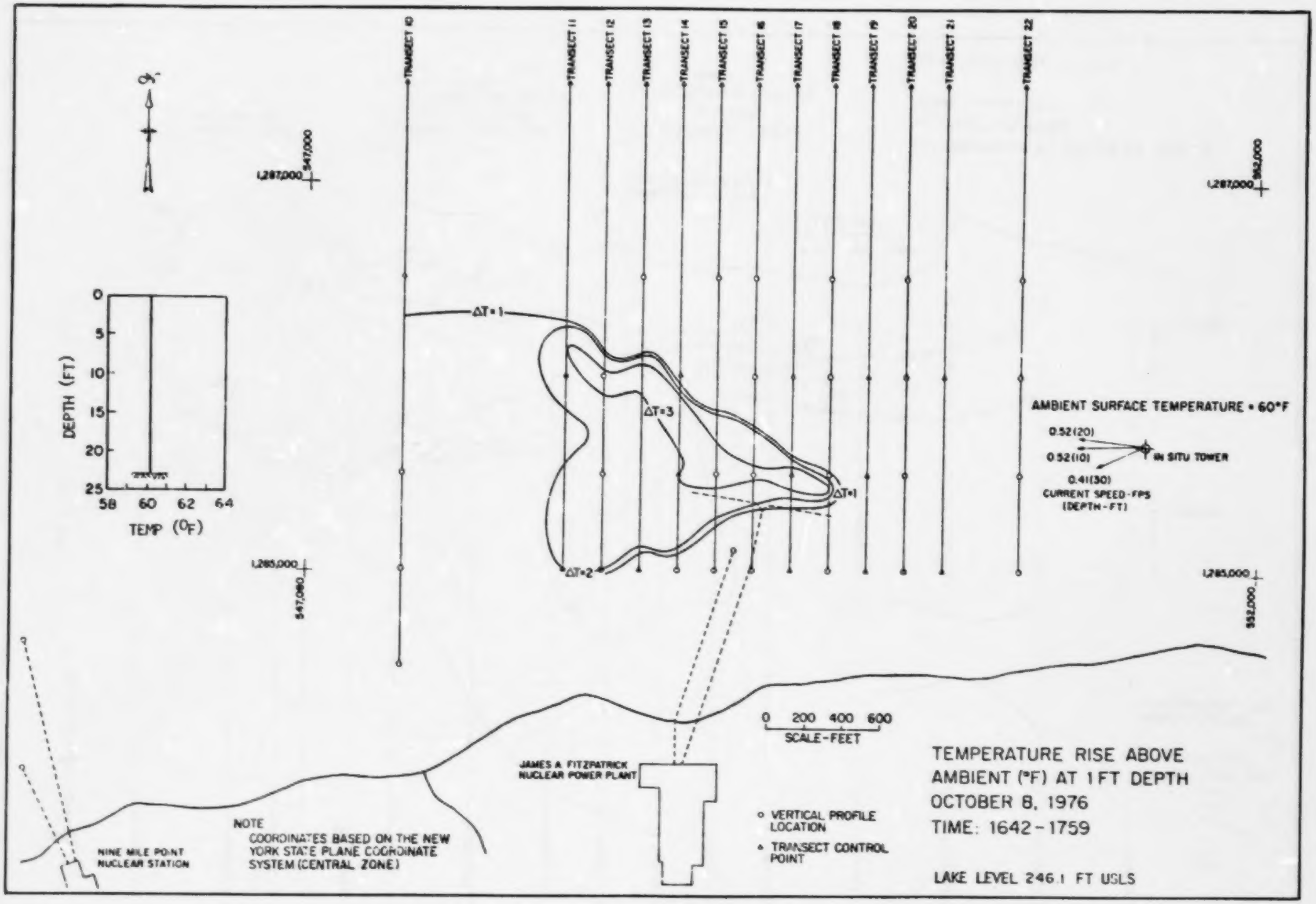
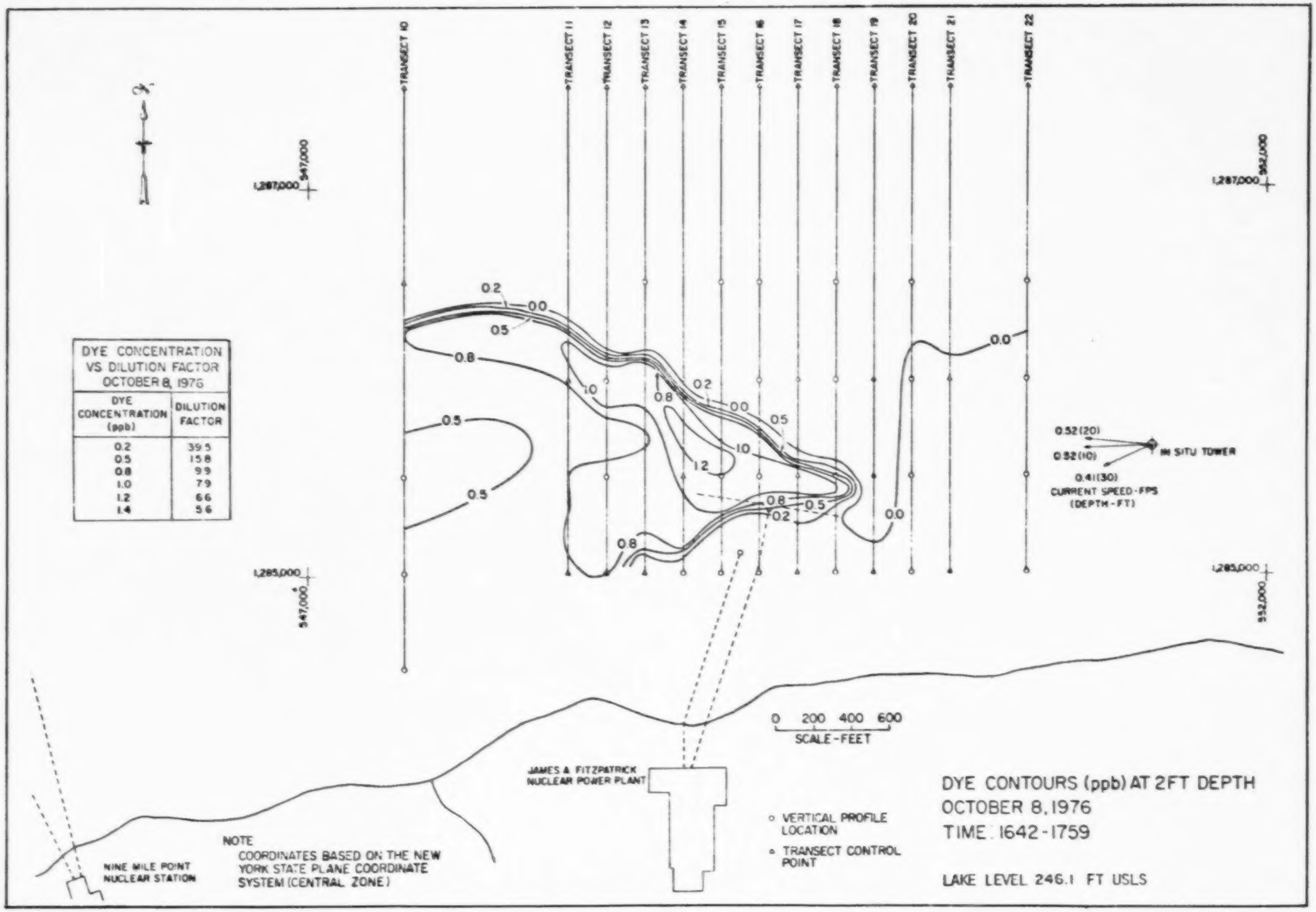

TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
1,287,000 547,000
1,285,000 547,080
1,287,000 552,000
1,285,000 552,000
DEPTH (FT)
0
5
10
15
20
25
58
60
62
64
TEMP (°F)
ΔT=1
ΔT=3
ΔT=2
ΔT=1
AMBIENT SURFACE TEMPERATURE = 60°F
0.52(20)
0.52(10)
IN SITU TOWER
0.41(30)
CURRENT SPEED-FPS (DEPTH-FT)
0 200 400 600
SCALE-FEET
JAMES A. FITZPATRICK NUCLEAR POWER PLANT
NINE MILE POINT NUCLEAR STATION
NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)
○ VERTICAL PROFILE LOCATION
• TRANSECT CONTROL POINT
TEMPERATURE RISE ABOVE AMBIENT (°F) AT 1 FT DEPTH
OCTOBER 8, 1976
TIME: 1642-1759
LAKE LEVEL 246.1 FT USLS

Figure 11. Homogeneous Lake Condition - Temperature


TRANSECT 10
TRANSECT 11
TRANSECT 12
TRANSECT 13
TRANSECT 14
TRANSECT 15
TRANSECT 16
TRANSECT 17
TRANSECT 18
TRANSECT 19
TRANSECT 20
TRANSECT 21
TRANSECT 22
1,287,000
547,000
1,285,000
547,000
1,287,000
552,000
1,285,000
552,000
0.2
0.0
0.5
0.8
1.0
0.5
0.5
0.8
0.2
0.0
0.5
1.0
1.2
0.8
0.2
0.5
0.8
0.0
0.0
0.52(20)
0.52(10)
0.41(30)
CURRENT SPEED-FPS
(DEPTH-FT)
IN SITU TOWER
0 200 400 600
SCALE-FEET
JAMES A. FITZPATRICK
NUCLEAR POWER PLANT
NINE MILE POINT
NUCLEAR STATION
○ VERTICAL PROFILE LOCATION
• TRANSECT CONTROL POINT

DYE CONCENTRATION VS DILUTION FACTOR OCTOBER 8, 1976

DYE CONCENTRATION (ppb)	DILUTION FACTOR
0.2	395
0.5	158
0.8	99
1.0	79
1.2	66
1.4	56

DYE CONTOURS (ppb) AT 2FT DEPTH
OCTOBER 8, 1976
TIME: 1642-1759

LAKE LEVEL 246.1 FT USLS

NOTE
COORDINATES BASED ON THE NEW YORK STATE PLANE COORDINATE SYSTEM (CENTRAL ZONE)

Figure 12. Homogeneous Lake Condition - Dye

435<
21

omit

NUM. MOD. II

X-B-71

ABSTRACT

Observations of Thermal Plumes from Submerged Discharges in the Great Lakes and Their Implications for Modeling and Monitoring

by
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Water Resources Research Program
Energy and Environmental Systems Division
Argonne National Laboratory

A study of the physical aspects of waste heat disposal by means of submerged discharges into large bodies of water has been undertaken by Argonne National Laboratory (ANL) for the U.S. Energy Research and Development Administration. The objective of this study is an evaluation of modeling techniques, both mathematical and physical, for the prediction of the temperature fields created by submerged discharges. Initial phases of this study involve the acquisition of data regarding the three-dimensional structure of temperature fields at prototype scales at submerged discharges from power plants on the Great Lakes.

The measurement of the three-dimensional temperature structure in the vicinity of a power plant is accomplished by means of a thermistor boom or towed thermistor cable suspended from a moving boat, the instantaneous location of which is determined by a microwave ranging system. During temperature surveys, ambient temperatures and currents are recorded at moored thermograph and current-meter stations and by vertical profiling. Discharge temperatures are continuously monitored in the plant. Typical results of such temperature surveys include horizontal plots of isotherms at 0.5 or 1.0m vertical intervals and cross-sectional plots of isotherms in the near- and far field regions.

Thermal plumes from submerged discharges at three sites have been studied for a variety of receiving water conditions. The discharges studied are from the Zion Nuclear Power Station on the western shore of Lake Michigan, the Donald C. Cook Nuclear Power Plant on the eastern shore of Lake Michigan, and the James A. Fitz Patrick Nuclear Power Plant on the southern shore of Lake Ontario. Though all dis-

charges are submerged, the discharge structure geometrics and depths of receiving waters differ. At the Zion Plant, two box-like structures, approximately 100m apart, discharge from slots on their off-shore and outer faces into about 3.7m of water. The discharge at the Cook site consists of two adjacent slots discharging into about 5.7m of water. The Fitz Patrick discharge is an offshore-directed, multiport diffuser, consisting of twelve round jets, located in about 9.8m of water.

Examples from the results of the field measurements at these sites are used to indicate:

1) the differing regimes of flow for the different submerged discharges,
2) the variations in plume behavior at a particular site with changes in discharge and receiving water conditions,
3) the effect of two discharges in close proximity to each other, and
4) some comparisons of prototype behavior with model predictions.

The examples demonstrate the temporal and spatial varability of the receiving water environment and related of the plume behavior. This varability has important implications regarding the modeling of submerged thermal discharges, the comparisons of prototype data with model predictions, the design of monitoring systems and, the interpretation of monitoring results for thermal discharges.

20-45-29

X-B-73

AN ANALYSIS OF THE THERMAL MONITORING DATA COLLECTED AT THE PEACH BOTTOM ATOMIC POWER STATION

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Nuclear Regulatory Research of the
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Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

A comprehensive study of the data collected as part of the environmental technical specifications program for Units 2 and 3 of the Peach Bottom Atomic Power Station was conducted for the Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission. The study included an analysis of both the hydrothermal and ecological data collected from 1967 through 1976. This paper presents the details of the hydrothermal analysis performed under this program.

The two primary methods used for temperature monitoring, during both the preoperational and operational periods of the program, are a fixed thermograph network and boat survey measurements. Analysis of the boat survey data provides a fine resolution demonstrating variations in ambient temperature in Conowingo Pond, as well as providing a qualitative picture of the thermal plume produced by the Peach Bottom thermal discharge. The data from 18 thermograph stations was used for a quantitative probability analysis.

INTRODUCTION

A licensing requirement for nuclear power plants is the establishment of an environmental monitoring program. The purpose of these programs is to ensure that nuclear power plants are operated without causing unforeseen environmental damage. Considerable time, effort, and money are being spent by utilities to accumulate monitoring data. However, to determine the effectiveness of these monitoring programs, it is necessary to analyze the monitoring data collected.

In response to this, the U. S. Nuclear Regulatory Commission, Office of Regulatory Research established the Technical Specifications Review program. Some of the objectives of this program were to validate impact predictions made in the Final Environmental Statement, to evaluate the adequacy of the preoperational and operational monitoring programs, and to recommend standardized procedures in data collection and analysis. As part of the Technical Specifications Review program, Oak Ridge National Laboratory has reviewed the hydrothermal and ecological monitoring programs at three operating power plants [1, 2, 3, 4]. Additional plants were reviewed by the staff of Argonne National Laboratory and Battelle Pacific Northwest Laboratory, references to these reports may be found in references 1-4.

This paper presents the details and results of the analysis performed on the hydrothermal monitoring data collected at Peach Bottom Atomic Power Station, located on Conowingo Pond in Pennsylvania. The first three sections of this paper present background information describing the Peach Bottom plant and its operating history, the hydrology of Conowingo Pond, and the hydrothermal monitoring program. For more details, the reader is directed to the complete report of the analysis [3]. The data analysis section of this paper presents a discussion of the information obtained from the boat surveys, the methodology for analyzing the thermograph data, and the results of a probability analysis. The final section contains concluding remarks regarding the relative merits of this monitoring program, as well as recommendations for future monitoring programs, based on the experience gained from this study.

PLANT DESIGN AND OPERATING HISTORY

Peach Bottom Atomic Power Station (PBAPS) is a three reactor installation operated by Philadelphia Electric Company. Unit 1 was an experimental high-temperature gas-cooled reactor which is now decommissioned. Units 2 and 3 each consists of a General Electric boiling-water reactor with a rated core thermal power of 3293 MW(t) and a design core thermal power of 3440 MW(t). Each unit has a rated net electrical output of 1065 MW(e) and design net electrical output of 1100 MW(e). The total heat rejected to the environment, by both units, is 4456 MW(t) at rated conditions and 4680 MW(t) at design conditions.

Unit 1 reached initial criticality in March 1966 and was shut down for decommissioning in November 1974. Unit 2 achieved initial criticality in September 1973 and began commercial operation in May 1974. Unit 3 achieved initial criticality in August 1974 and began commercial service in December 1974. The power levels of Units 2 and 3 have been quite variable since the commencement of operation. This is because of restrictions resulting from a generic BWR design problem including vibration of in-core monitoring devices. This problem is reflected in the heat rejection rates. Monthly averaged heat rejection rates [5,6] from the combined units during 1974 and 1975 are shown in Fig. 1. The only time during this period that the station approached rated capacity was in March and April 1975.

The heat rejected by PBAPS is dissipated by a once-through cooling system with optional helper cooling towers. The PBAPS cooling water pathway is illustrated in Fig. 2. At full operation, 3342 cfs of makeup water is drawn from Conowingo Pond. After passing through trash racks and traveling screens, this makeup water flows 700 ft, through separate intake basins, to a shoreline pumphouse. The water is then passed through the condensers where it experiences a 19.9°F temperature rise at rated conditions, and a 20.8°F temperature rise at design conditions. Subsequently, the heated water is discharged into a common intermediate pond.

A portion of the discharge flow proceeds directly into a 4700-ft-long discharge canal, which extends southward from the plant and parallels the shoreline. Approximately 58% of the condenser effluent can be diverted directly from the intermediate basin through mechanical-draft helper cooling towers prior to entering the discharge canal. Because the performance of the cooling towers depends on meteorological conditions, their effectiveness in dissipating heat is subject to wide variations. On an annual basis, these towers can reduce the heat load of Conowingo Pond by 25%. Up to 29 cfs of water can be lost from the cooling towers through evaporation and drift.

The heated water is delivered to Conowingo Pond via a discharge control structure located at the end of the discharge canal. This discharge structure consists of four sluice gates arranged in a rectangular pattern. One gate is permanently open, and the position of the other three is automatically controlled to maintain a discharge velocity of 5 to 8 fps.

SITE HYDROLOGY

The Peach Bottom Atomic Power Station is located in southeastern Pennsylvania on the west bank of Conowingo Pond. This pond is an impounded reach of the Susquehanna River; bounded by Holtwood Dam to the north, in Pennsylvania, and bounded by Conowingo Dam to the south, in Maryland, as shown in Fig. 3.

Conowingo Pond is 14 miles long, with the width varying from 0.5 to 1.5 miles. The surface area of the pond is about 13.5 sq miles, and the pond volume varies between 240,000 and 322,000 acre-ft. Normal depths are 10 to 20 ft in the upper 9 miles of the pond, then sloping to a depth of about 90 ft at the base of Conowingo Dam. The Peach Bottom station is located approximately 6 miles downstream (south) of the Holtwood Dam, and the pond width at the site is approximately 1.3 miles.

The structure of the flow within and through Conowingo Pond is quite complex as a result of the plurality and variability of regulated inflows and outflows. The most significant of these are the inflow through the Holtwood Hydroelectric Plant, the outflow through the Conowingo Hydro Plant, and flow in both directions between Conowingo Pond and the Muddy Run Pump Storage facility. Figure 4 shows a normal seven-day cycling operation of these three hydroelectric plants. It is apparent from this figure that the circulation pattern in Conowingo Pond varies with the time of day as well as the day of the week.

Water temperature in Conowingo Pond varies considerably during the course of a year. Summer temperatures are typically near 80°F, with vertical stratification in the deep area near Conowingo Dam. The maximum surface temperature measured during the PBAPS preoperational survey period was 94°F. Winter temperatures are typically below 35°F, and the pond usually has ice cover during January and February.

HYDROTHERMAL MONITORING PROGRAM

A hydrothermal monitoring program in Conowingo Pond was initiated in December 1971 by Environmental Devices Corporation (ENDECO), for the Philadelphia Electric Company (PECO). The program consists of two major ongoing components: continuous monitoring by fixed thermographs and periodic boat surveys of the vertical temperature profile at selected stations. Along with this, a number of short-term supplementary projects, such as a current survey of Conowingo Pond, have been carried out. The early phase of the monitoring program is summarized in a preoperational report [7] including 1972 and the first half of 1973. Subsequently, monthly reports [5] have been issued.

The fixed monitors are ENDECO Type 109 recording thermographs, which take 1-hr time exposure photographs of a liquid-in-glass thermometer each hour. These thermographs have an accurance of ±0.4°F, a time constant of 10 min, and have provided very reliable service at Peach Bottom. Figure 5 shows the location of thermograph stations. At the inception of the monitoring program, thermographs were located at stations 1 through 18. The number of thermographs was increased to 35 in January 1974 but was reduced to 26 in December of that year. With a few exceptions, these locations have since remained unchanged. Most of the thermographs have their sensors mounted at a depth of 1 ft, to record surface temperatures. However, there are several near-bottom thermographs.

Figure 5 also shows the vertical profiling stations used in the thermal boat surveys. Originally, 44 stations were sampled, but by July 1974 the number of stations had increased to 72. Temperature readings at 1, 5, and 10 ft depths are made at each location using an ENDECO Type 133 digital thermometer. This device has an accurancy of ±0.4°F and a time constant of 3.6 sec. The sensor depth is determined from markings on the probe cable.

The number of boat surveys reported for each month has varied. The typical number per month is 6. Figure 6 shows the usual manner in which these results are presented. Horizontal isotherm plots are prepared for each depth, along with a vertical isotherm plot down the pond axis. The maps are accompanied by a rather complete list of relevant environmental parameters. The time required to complete a boat survey is typically 4 hr, although 7 hr runs are not uncommon.

DATA ANALYSIS

Data from both the boat surveys and the fixed thermographs were used to characterize and quantify the temperature distribution in Conowingo Pond during portions of the preoperational and operational periods of PBAPS. Thermograph data were provided by PECO in the form of a magnetic tape. This tape contained hourly surface temperature readings for 18 stations for a period beginning January 1, 1972 and extending into June 1976. The locations of these thermograph stations are shown in Fig. 5 as Stations 1 through 18. The boat survey data were taken from the PBAPS monthly reports [5]. Other pertinent information such as dam operations, plant heat rejection rates, and circulating water flow rates were available as strip charts in these monthly reports.

The high spatial resolution obtained by the boat surveys provides adequate data for defining the extent of the plume produce in Conowingo Pond by the discharge from PBAPS. The heated water is discharged parallel to the west bank and typically gives rise to a classical plume hugging the shore to the south of the discharge canal. This situation is illustrated in Fig. 6, which shows the iostherm maps from a boat survey. A striking feature in this figure is the downstream extent of the plume. While the plume is near the shore, it is quite well defined. However, at the state line, the west bank of the pond recedes. Beyond this point, the plume trajectory is towards the centerline of the pond. As the plume moves away from the shore, it is diluted and distorted, most likely by stronger flow, until a point is reached where it becomes a nebulous mass of warm water. This mechanism serves to reduce the extent of higher excess temperatures while making lesser excess temperatures difficult to identify. Figure 6 shows that surface water temperatures below the PBAPS discharge, and extending to the Conowingo Dam, are somehwat higher than the upstream surface temperatures. This cannot be singularly attributed to the PBAPS discharge since the hypolimnetic withdrawal of water through the Conowingo Dam also results in an increase in the surrounding surface water temperatures.

It is enlightening to investigate the relative influence of these two mechanisms on downstream temperature rise. To accomplish this, monthly averaged temperature differences, based on an upstream and a downstream location, were computed using all the boat survey data during a preoperational year. This procedure was then repeated for an operational year. The results of both these calculations are plotted in Figure 7. The preoperational curve exhibits an annual cycle in the temperature difference. In general, the greatest temperature differences occur during the summer months when ambient stratification exists, while the smallest differences occur during winter isothermal conditions. This supports the selective withdrawal hypothesis. Similar behavior is apparent in the operational curve. However, this curve is consistently higher than the preoperational one, with a mean difference of 1.7°F and a maximum difference of 3.7°F. This result strongly suggests that the thermal output from PBAPS produces an increase in temperature as far downstream as Conowingo Dam.

While the boat survey data provides valuable information on the general features of the PBAPS thermal plume, it is not well suited for mathematical analyses to precisely quantify the extent of the thermal loading. One drawback to this type of monitoring is the low sampling frequency and nonuniform intervals between samplings. A second deficiency of boat surveys is the lack of synopticity. The operation of the hydroelectric facilities can produce substantial changes in the flow in Conowingo Pond during the course of a day. Since the boat surveys typically take 4 hr to complete, some movement of the plume can be expected over this survey period.

The semi-qualitative information provided by the boat surveys is complimented by the time series data from the network of fixed thermographs. Unfortunately, the low spatial resolution afforded by 18 thermograph stations precludes the direct utilization of this data in quantifying the thermal loading from PBAPS. However, if these data could be manipulated to yield excess temperatures resulting from the PBAPS thermal discharge, valuable information could be obtained.

A precise knowledge of the ambient temperature as a function of time at each thermograph station is an obvious prerequisite in establishing excess temperature time series. A direct approach to this problem is to assume that an upstream thermograph is not influenced by the PBAPS discharge, and can, therefore, be taken as a control station. The temperature at this station is then subtracted from the temperatures at the other thermograph stations. Since the preoperational thermal study shows a definite increase in ambient temperature with downstream position in Conowingo Pond, this technique will produce erroneous excess temperatures.

A more systematic technique for establishing ambient temperatures was carried out for this study. The assumption is still that an upstream control station exists, however, a quadratic regression analysis is performed on the preoperational data to provide a set of algebraic equations for predicting the ambient temperatures at each station, based on the observed temperature at the control station. To resolve the temporal variations in the longitudinal ambient temperature differences, as illustrated in Figure 7, separate regression analyses were performed on a monthly basis.

Station 1 was selected for the control. This choice was based on inspection of isotherm maps from boat surveys. Stations 17 and 18 were not used in any analysis since they are not in the pond proper. The regression analyses were performed on preoperational data for the year beginning July 1, 1973, and ending June 30, 1974. This year was selected because it has the most complete preoperational data. During the latter part of this period there was some thermal discharge from PBAPS, however, the plant's output was low and no significant bias in the regression is expected. Figure 8 is an example of a curve fit obtained by the regression analyses. Ambient temperatures could not be reasonably predicted for Station 16 due to extensive scatter in the data. Consequently, this station is not included in the subsequent analyses.

A probability analysis was done on one year of operational data beginning July 1, 1975. This period was selected because it generally has the most complete data, particularly at Station 1. Excess temperatures were computed for each hourly temperature measurement at the 14 thermograph stations. Excess temperatures at every station were grouped into a 0.5°F slots extending over the entire range. The number of observations in each slot were counted and then normalized with the total number of observations made at that particular station. This provides an estimate of the probability distributions as a function of the excess temperature. These probability distributions at each station are plotted in Figure 9.

To comprehend the meaning of these distributions, it is necessary to reexamine the prediction of the ambient temperatures. The regression analysis provides a "best fit" to the observed data. An actual ambient temperature could, with equal probability, be greater than or less than the predicted ambient temperature. Furthermore, if the prediction is meaningful, the standard deviation should be small. Therefore, if a station is unaffected by the thermal discharge its temperature probability distribution should be characterized by a sharp symmetric peak centered at zero excess temperature. Referring to Figure 9, it becomes apparent that a number of stations fall into this category. In particular, Stations 2, 4, 5, and 12 show little evidence of excess temperature. Since Station 5 is located off the PBAPS intake, this result indicates that recirculation of the heated effluent is minimal.

Stations influenced by the thermal discharge should have probability distributions characterized by lower, but broader, curves displaced in the positive direction along the excess temperature axis. Good examples of such distributions are Stations 6, 7, 10, and 11. Station 6 shows the strongest influence because it is the nearest station to the discharge. The probability distribution at this station also shows that excess temperatures of 2°F to 10°F can occur at Station 6 with about the same likelihood. This is a result of variable plant thermal output and possibly the intermittent cooling tower operation.

Some thermograph stations show only slight temperature rises. These can be identified in Figure 9 as curves with maximum probabilities occuring at low excess temperatures, and sloping more steeply on the negative side than the positive side. This situation appears at Stations 13, 14, and 15, and, to a lesser extent, Station 8.

The probability distribution for Station 9 has a near zero mean but no well defined maximum. Consequently, it is difficult to make definite remarks regarding the excess temperature at this station. Perhaps the ambient temperature predictions are inadequate at this station. The probability distribution for Station 3 is somewhat unusual. This station is located near the east bank of Conowingo Pond and is, therefore, not expected to exhibit any influence from PBAPS. This expectation is consistent with the probability distribution, however, this curve has an unexpected secondary peak centered at 3.5°F. Station 3 is adjacent to the mouth of a small creek, and this peak is possibly the result of periodic warm water inflows from this minor tributary.

These probability distributions are most useful for a station-by-station analysis. For viewing the pond as a whole, the cumulative distribution function (CDF) is more useful. The cumulative distribution function, in this application, is the probability of the excess temperature being less than a prescribed value. A CDF is determined by integrating the appropriate probability distribution.

The cumulative distribution function for Stations 2 through 15 have been calculated. One method to simultaneously present the CDFs for all stations is to enter the value of the CDF, corresponding to a fixed value for the excess temperature, at the appropriate locations on a map of Conowingo Pond. Contours of constant values for the CDFs can then be drawn to produce excess temperature probability envelopes for particular values for the excess temperature. Figure 10 was generated in this manner. To illustrate the interpretation of these plots, consider Figure 10(d) which shows contours of the CDF for an excess temperature of 3°F. It is apparent here that the 3°F excess temperature does not reach Station 10 75% of the time, and does not reach Station 7 50% of the time.

Unfortunately, the small number of thermograph stations results in rather sparse contours in Figure 10. Also, the boat survey information plus a certain creativity was required to draw the ones that are shown. However this figure does show that excess temperatures are most frequently observed in a well defined thermal plume region, which lies along the western shore of Conowingo Pond extending from the PBAPS discharge to Station 13. Downstream excess temperatures greater than 1°F only occurred east of the pond centerline 25% of the time. Excess temperatures exhibit larger cross stream extents directly off the PBAPS site. These conditions probably occurred when the Muddy Run Pump Storage operation produced a backflow in Conowingo Pond. In any case, this is a low probability occurrence.

CONCLUSIONS

The hydrothermal monitoring program at PBAPS has been, on the whole, quite ambitious and reasonably complete. While the information from the boat surveys is not synoptic, it proved valuable in establishing both the preoperational thermal characteristics of Conowingo Pond and the general downstream thermal loading during the PBAPS operation. The probability analysis performed on the thermograph data shows that the maximum observed excess temperatures are most common in a short thermal plume along the west bank of Conowingo Pond extending downstream from the PBAPS discharge.

One deficiency of the thermograph data is the poor spatial resolution provided by the 18 fixed thermographs. The deployment of more instruments, that occurred in the beginning of 1974, has limited value since there is insufficient preoperational data to adequately predict ambient temperatures during plant operation. In retrospect, the PBAPS thermal monitoring program could have provided more useful data, if the 35 thermograph stations were in existence during at least one full year of the preoperational period. With this, the boat survey operation could have been curtailed or eliminated.

The only major inadequacy of the PBAPS monitoring program is the in-plant data collection. Important plant operating parameters, such as cooling tower operation and temperature rise across the condensers, should be sampled with at least the same frequency as the thermographs. In addition, the in-plant instrumentation should be periodically checked for calibration. One important assessment that could not be made in this study, due to lack of data, is the effectiveness of the cooling towers in reducing the heat load to Conowingo Pond.

It is hoped that this study will serve to aid utilities and regulating agencies in designing thermal monitoring programs. To make maximum use of the data collected during such programs, it is recommended that data analysis methods be considered prior to establishing the monitoring program.

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5. Philadelphia Electric Company, Peach Bottom Atomic Power Station, Thermal and Biological Monitoring Program Monthly Reports, No. 1 (July 1973) through No. 31 (January 1976).

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7. Brainard, E.C., et al., Preoperational Thermal Monitoring Program for Conowingo Pond -- Peach Bottom Atomic Power Station Units 2 and 3. ENDECO Report 1004, March 1974.

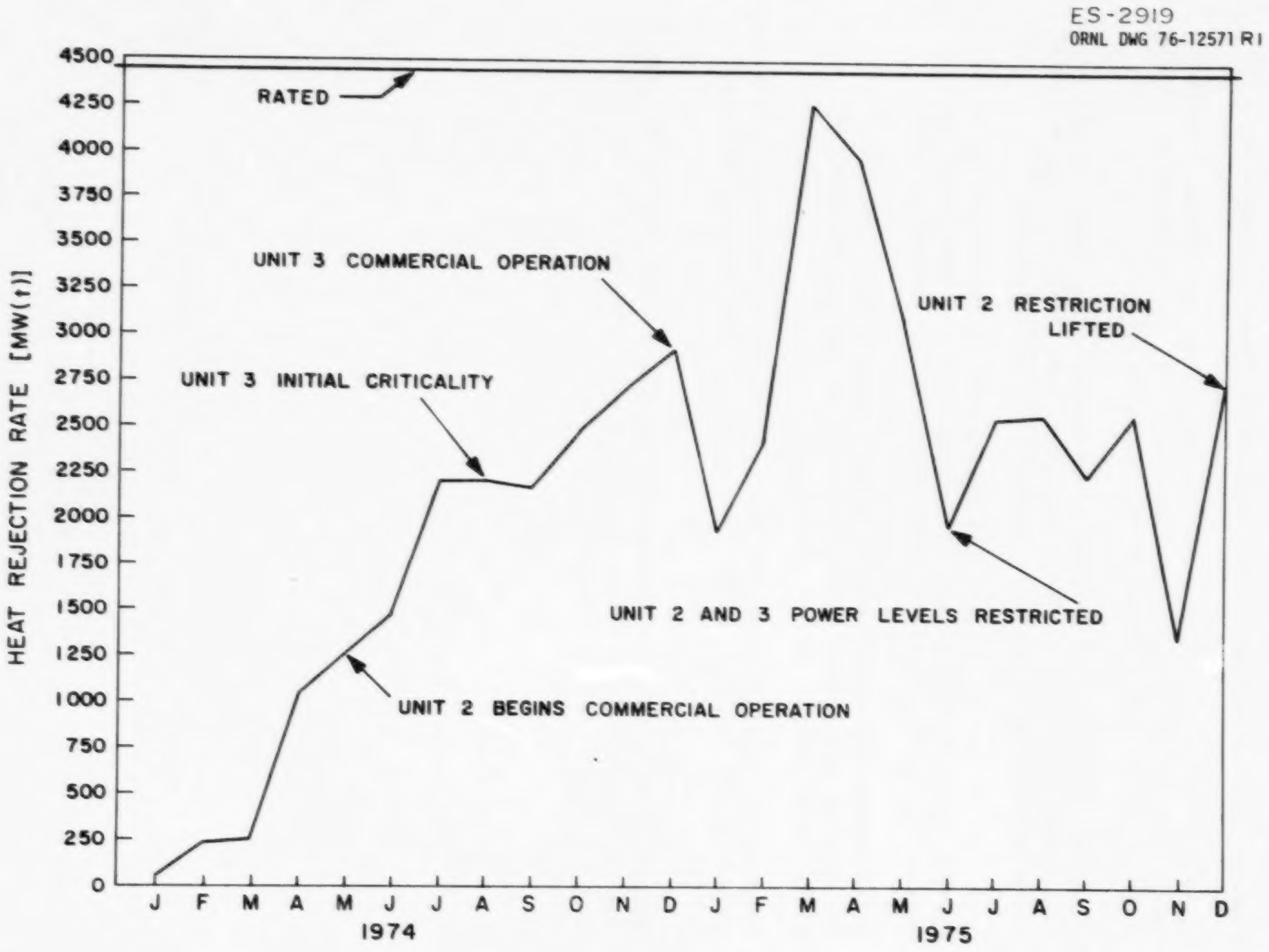

Fig. 1. Monthly average heat rejection rate (to air and water).

ORNL DWG 76-12553

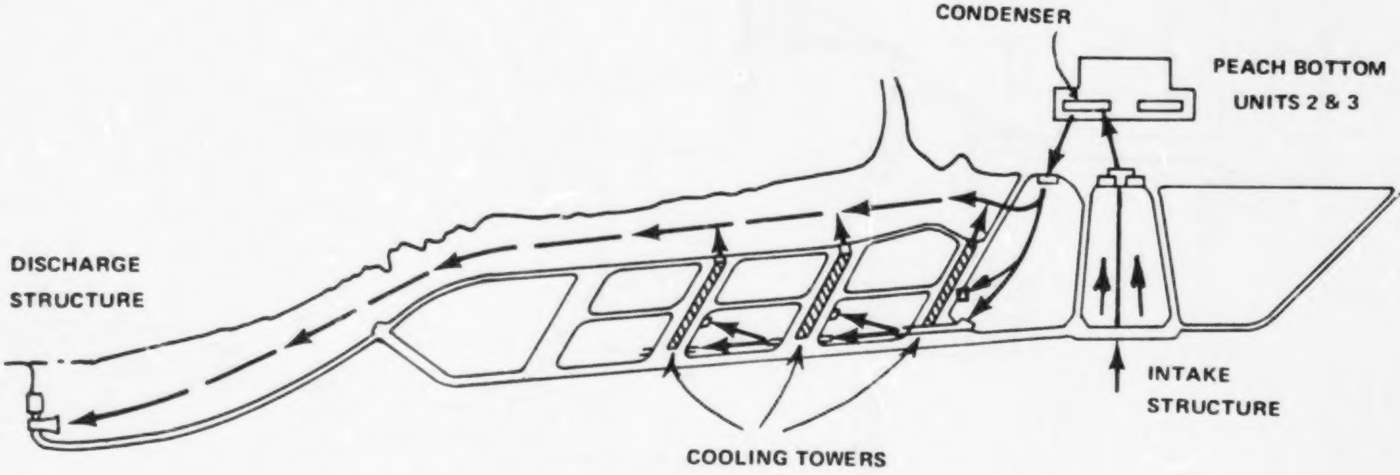
CONDENSER
PEACH BOTTOM
UNITS 2 & 3
DISCHARGE
STRUCTURE
INTAKE
STRUCTURE
COOLING TOWERS

Fig. 2. Path of cooling water from Conowingo Pond through the Peach Bottom Station. Source: Philadelphia Electric Company, *316(a) Demonstration for PBAPS Units 2 and 3 on Conowingo Pond* (July 1975).

AJW [illegible]

450<

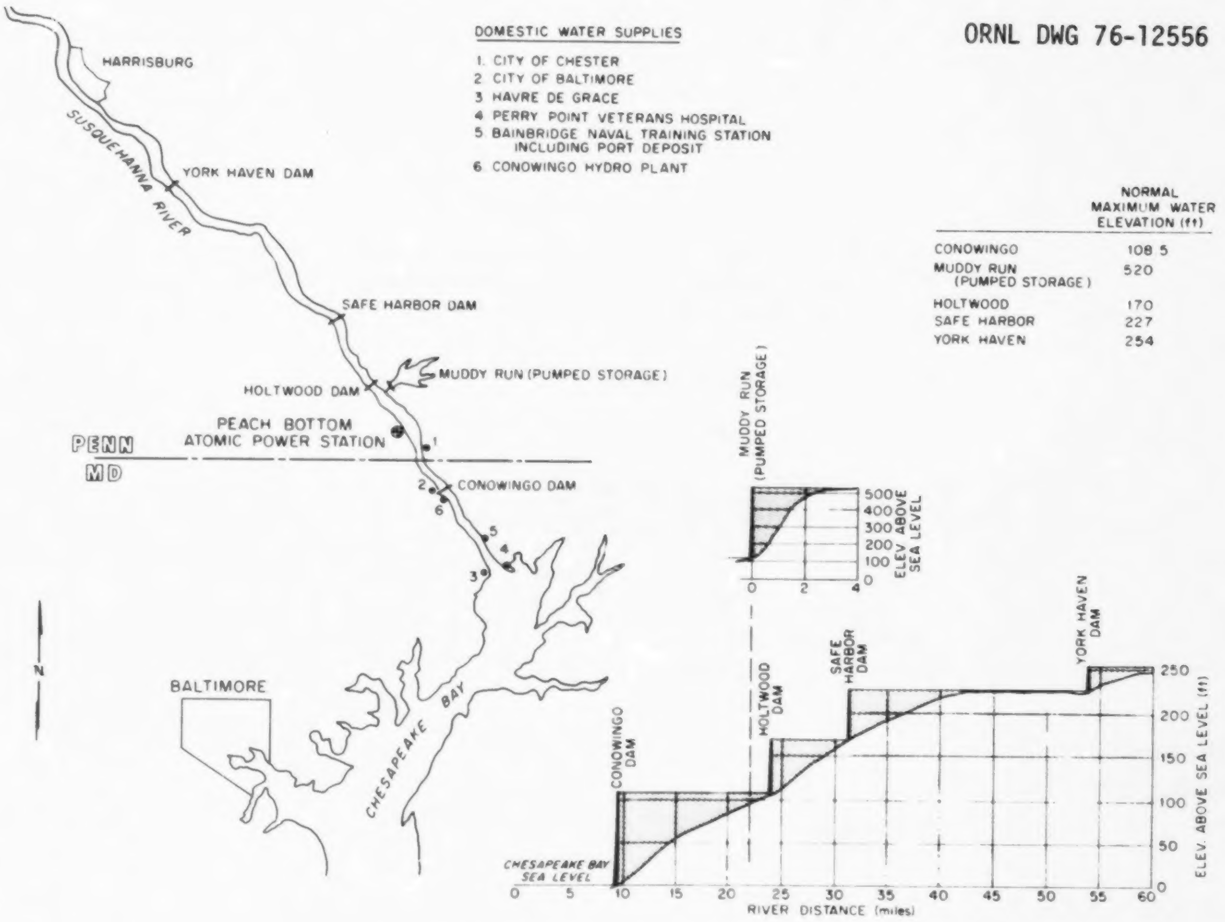
ORNL DWG 76-12556
DOMESTIC WATER SUPPLIES
1. CITY OF CHESTER
2. CITY OF BALTIMORE
3. HAVRE DE GRACE
4. PERRY POINT VETERANS HOSPITAL
5. BAINBRIDGE NAVAL TRAINING STATION INCLUDING PORT DEPOSIT
6. CONOWINGO HYDRO PLANT
NORMAL MAXIMUM WATER ELEVATION (ft)
CONOWINGO 108.5
MUDDY RUN (PUMPED STORAGE) 520
HOLTWOOD 170
SAFE HARBOR 227
YORK HAVEN 254
HARRISBURG
SUSQUEHANNA RIVER
YORK HAVEN DAM
SAFE HARBOR DAM
MUDDY RUN (PUMPED STORAGE)
HOLTWOOD DAM
PEACH BOTTOM ATOMIC POWER STATION
PENN
MD
CONOWINGO DAM
BALTIMORE
CHESAPEAKE BAY
N
MUDDY RUN (PUMPED STORAGE)
ELEV ABOVE SEA LEVEL
500
400
300
200
100
0
0
2
4
CONOWINGO DAM
HOLTWOOD DAM
SAFE HARBOR DAM
YORK HAVEN DAM
CHESAPEAKE BAY SEA LEVEL
ELEV. ABOVE SEA LEVEL (ft)
250
200
150
100
50
0
RIVER DISTANCE (miles)
0
5
10
15
20
25
30
35
40
45
50
55
60

Fig. 3. Hydraulic facilities on the lower Susquehanna River.
Source: Directorate of Licensing, U.S. Atomic Energy Commission, *Final Environmental Statement – Peach Bottom Atomic Power Station Units 2 and 3*, Docket Nos. 50-277 and 50-278 (April 1973).

ORNL DWG 76-12559

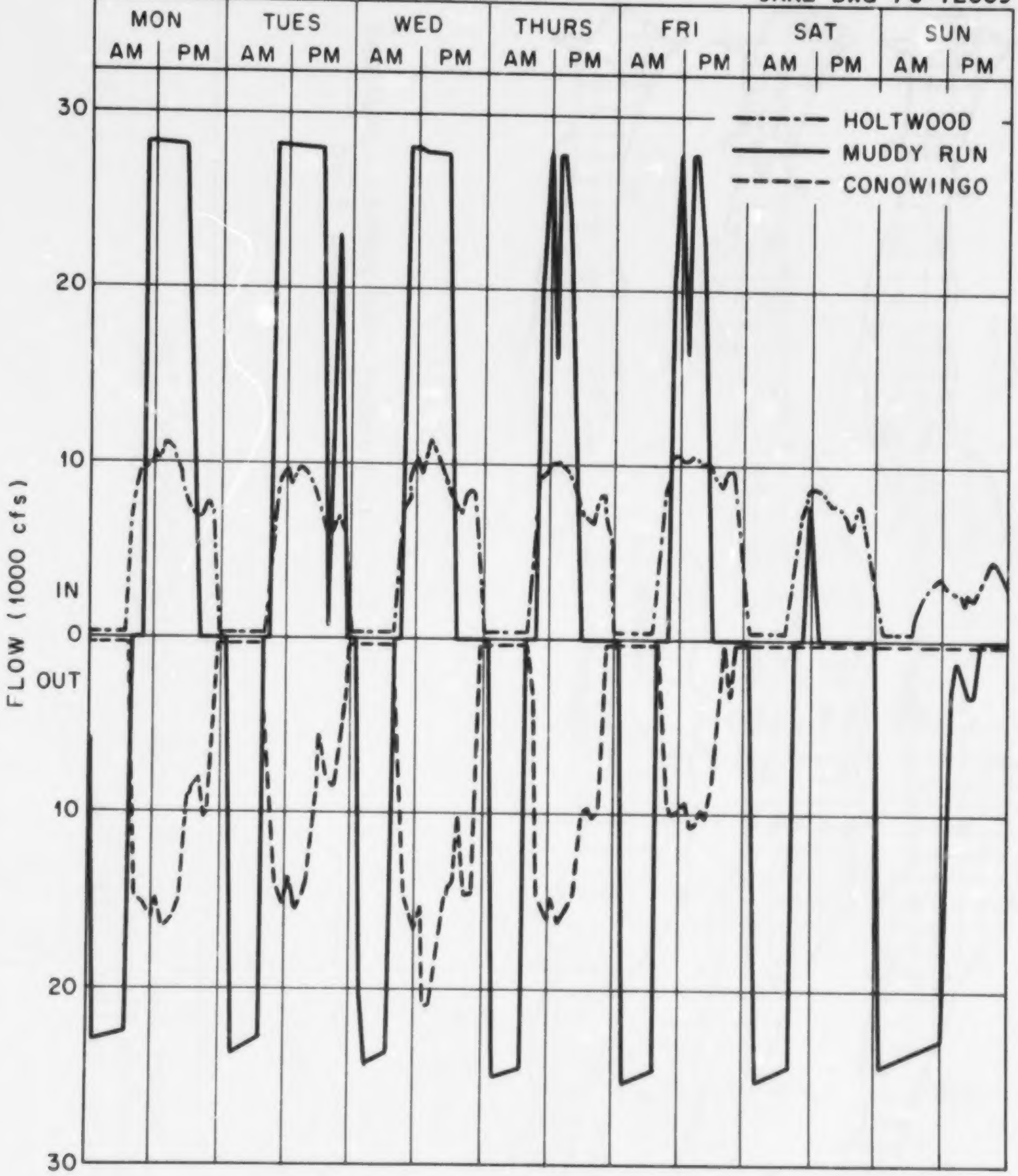

Fig. 4. Major weekly inflows and discharges of Conowingo Pond at a natural river flow of 5000 cfs. Source: Directorate of Licensing, U.S. Atomic Energy Commission, *Final Environmental Statement — Peach Bottom Atomic Power Station Units 2 and 3*, Docket Nos. 50-277 and 50-278 (April 1973).

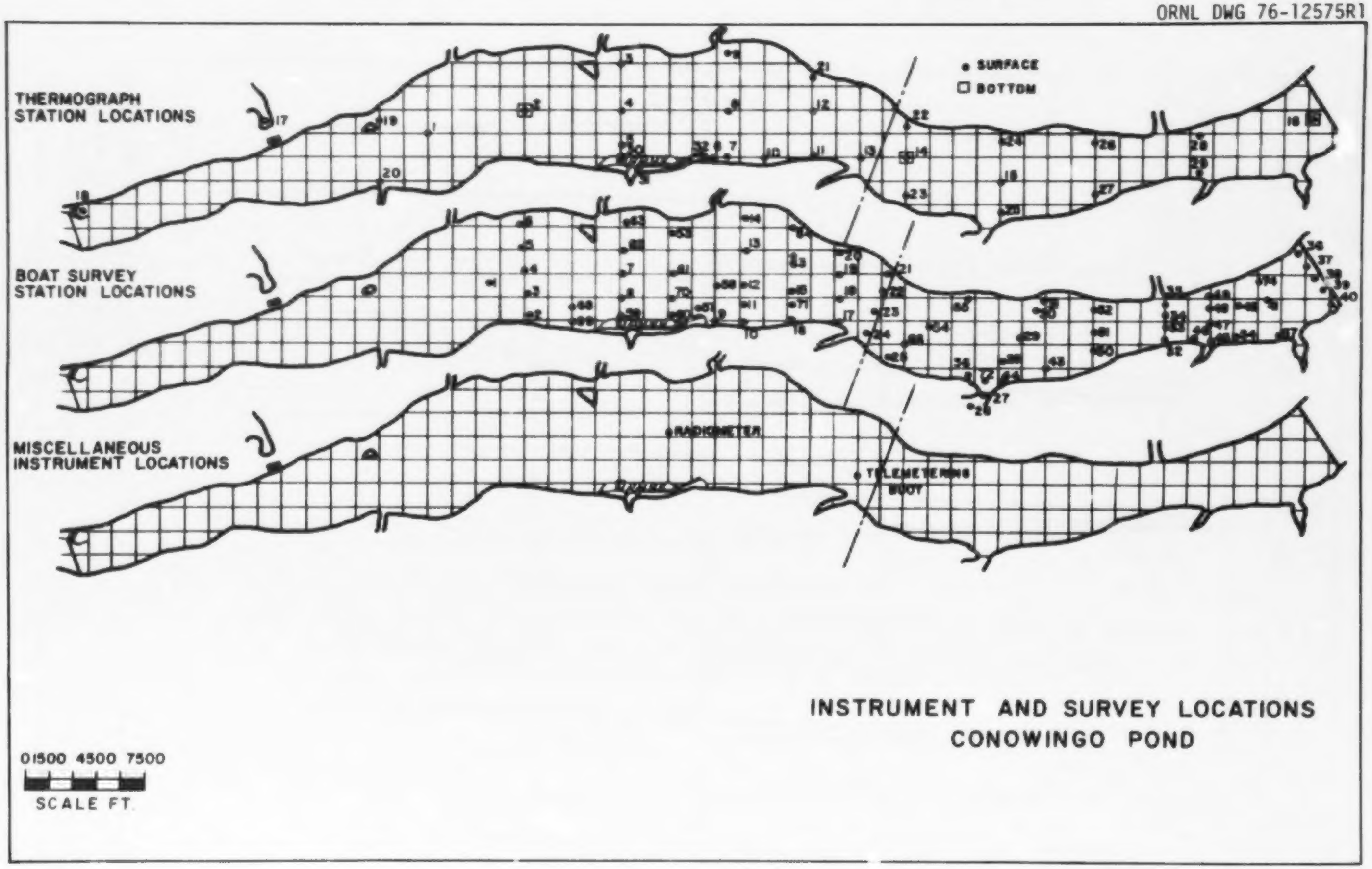
ORNL DWG 76-12575R1
THERMOGRAPH STATION LOCATIONS
BOAT SURVEY STATION LOCATIONS
MISCELLANEOUS INSTRUMENT LOCATIONS
SURFACE
BOTTOM
RADIOMETER
TELEMETERING BUOY
INSTRUMENT AND SURVEY LOCATIONS
CONOWINGO POND
0 1500 4500 7500
SCALE FT.

Fig. 5. ENDECO temperature monitoring locations in Conowingo Pond.
Source: Philadelphia Electric Company, *Peach Bottom Atomic Power Station Monthly Report No. 25* (July 1975), Fig. 2.1-1.

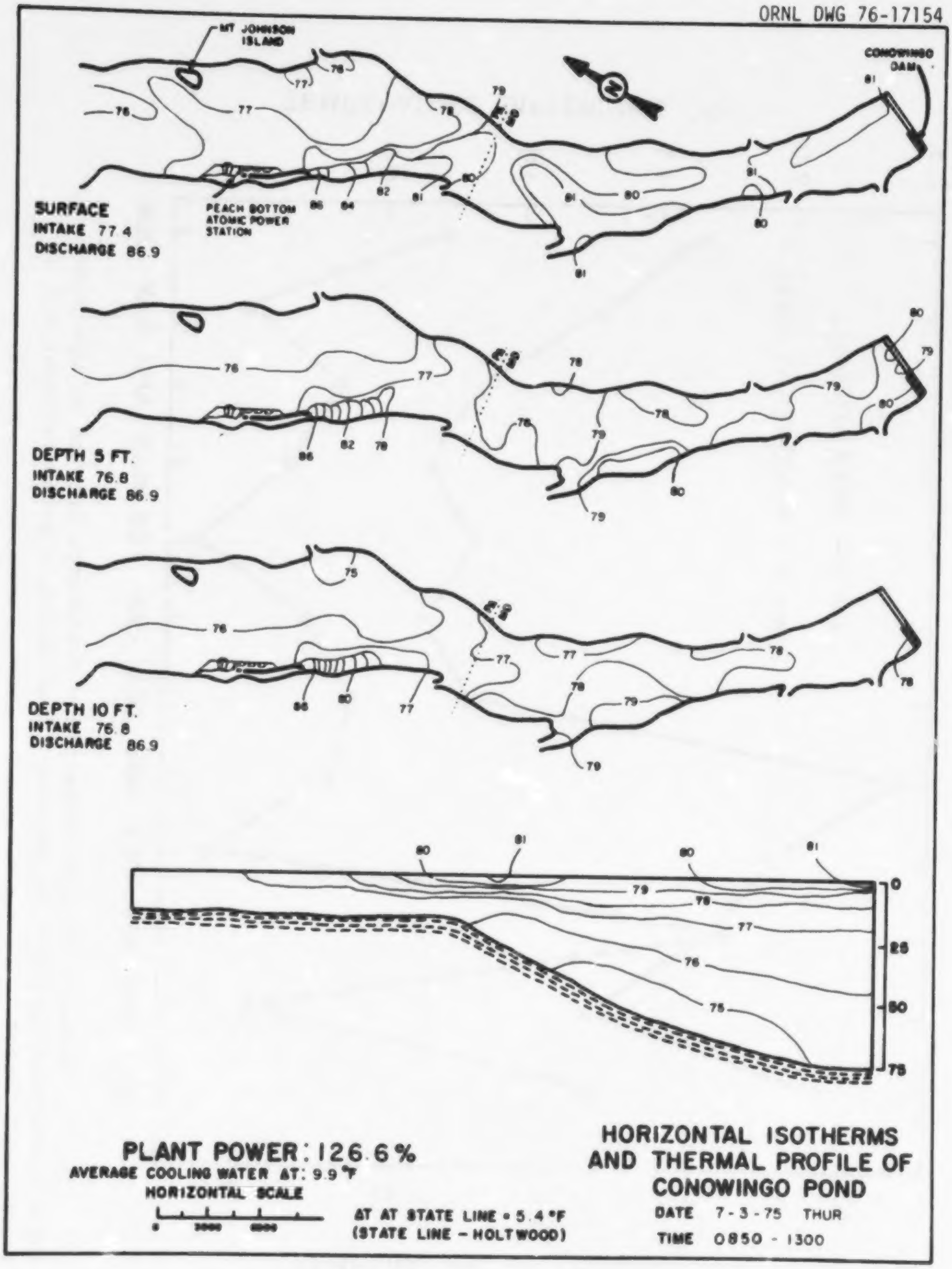
ORNL DWG 76-17154
MT JOHNSON ISLAND
CONOWINGO DAM
SURFACE
INTAKE 77.4
DISCHARGE 86.9
PEACH BOTTOM ATOMIC POWER STATION
DEPTH 5 FT.
INTAKE 76.8
DISCHARGE 86.9
DEPTH 10 FT.
INTAKE 76.8
DISCHARGE 86.9
0
25
50
75
PLANT POWER: 126.6%
AVERAGE COOLING WATER ΔT: 9.9°F
HORIZONTAL SCALE
0 3000 6000
ΔT AT STATE LINE = 5.4°F
(STATE LINE - HOLTWOOD)
HORIZONTAL ISOTHERMS AND THERMAL PROFILE OF CONOWINGO POND
DATE 7-3-75 THUR
TIME 0850 - 1300

Fig. 6. Horizontal isotherms and thermal profile of Conowingo Pond. Source: Philadelphia Electric Company, *Peach Bottom Atomic Power Station Monthly Report No. 25* (July 1975), Fig. 2.4-5.

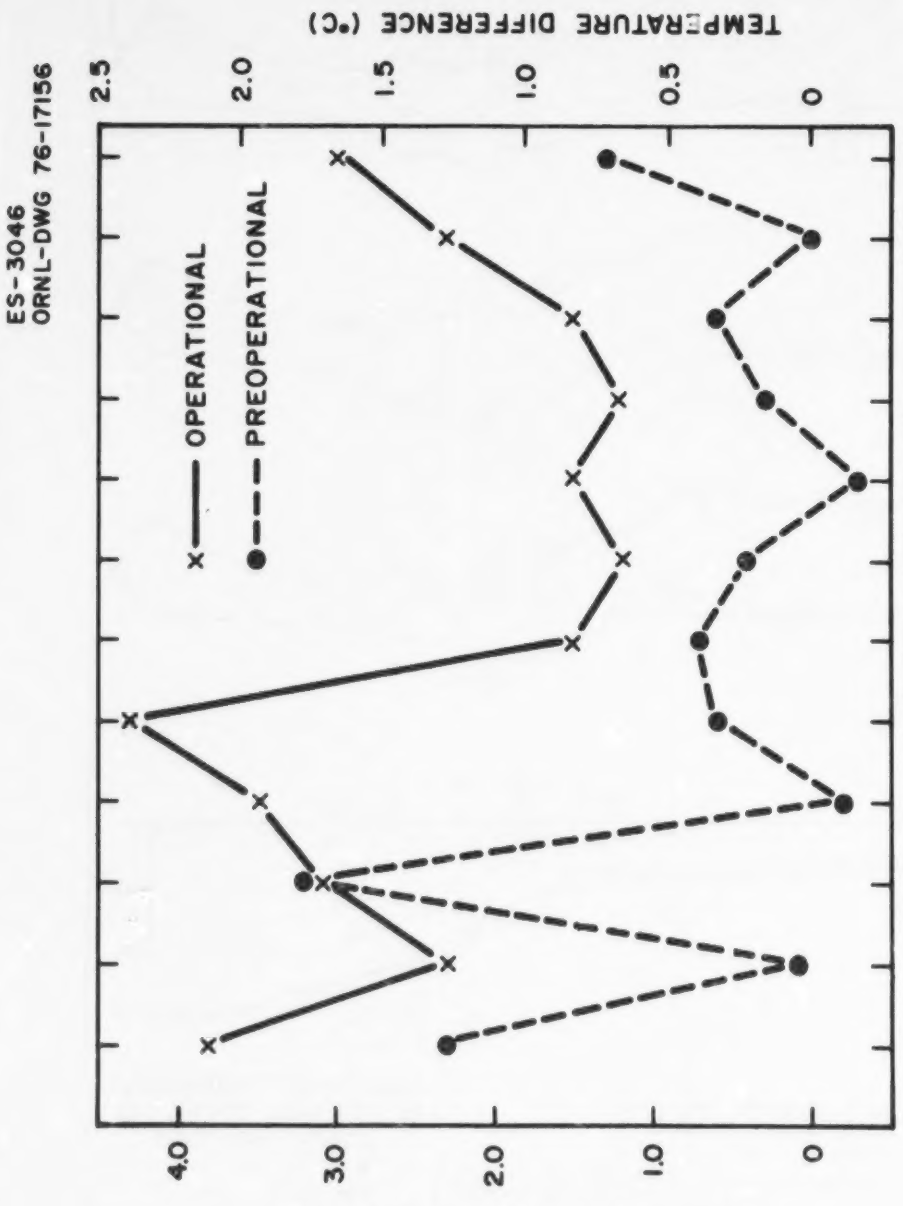

Fig. 7. Monthly-averaged temperature difference between an upstream and a downstream location in Conowingo Pond during a preoperational and an operational period.

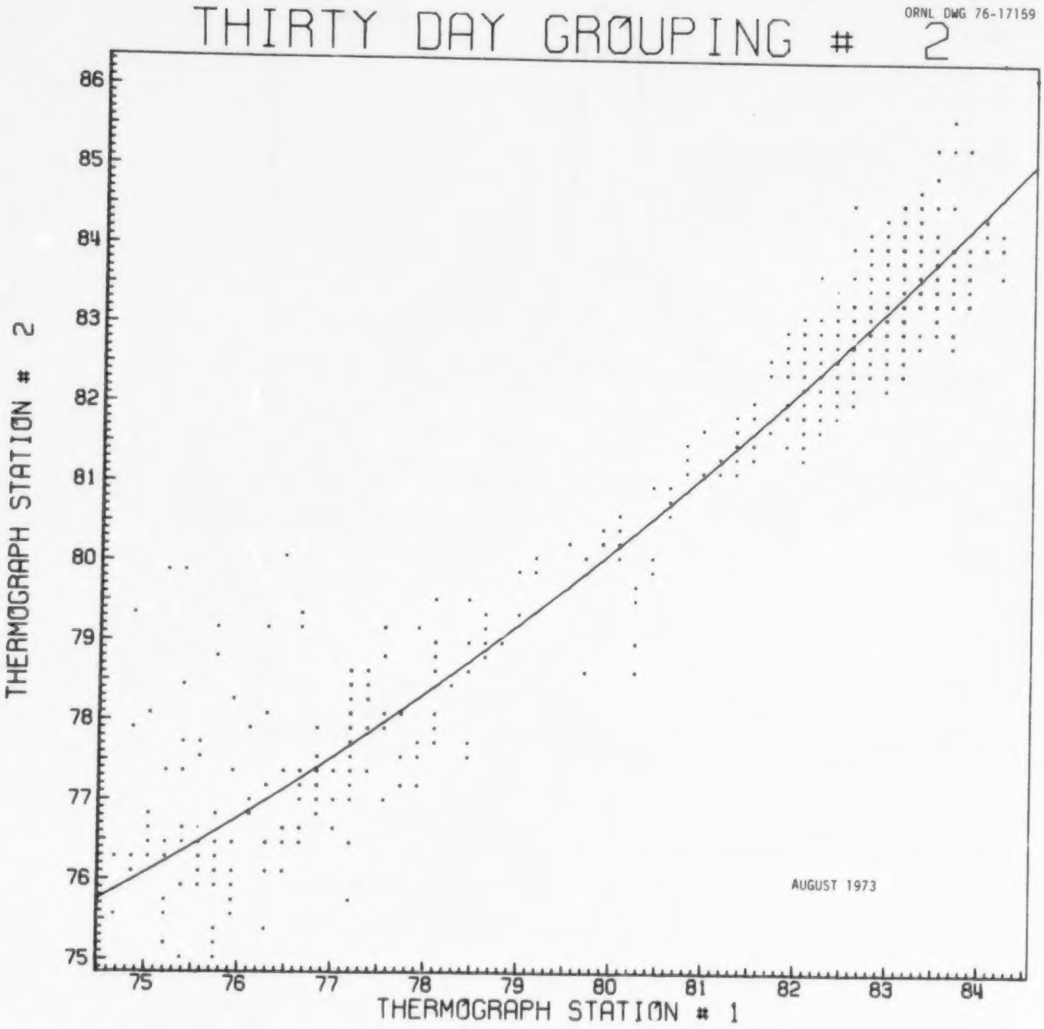

Fig. 8. Monthly (August) predictive curve for the ambient temperature (°F) at station 2 as determined by the regression analysis. The observed data at station 2 plotted against the observed data at station 1 are also shown.

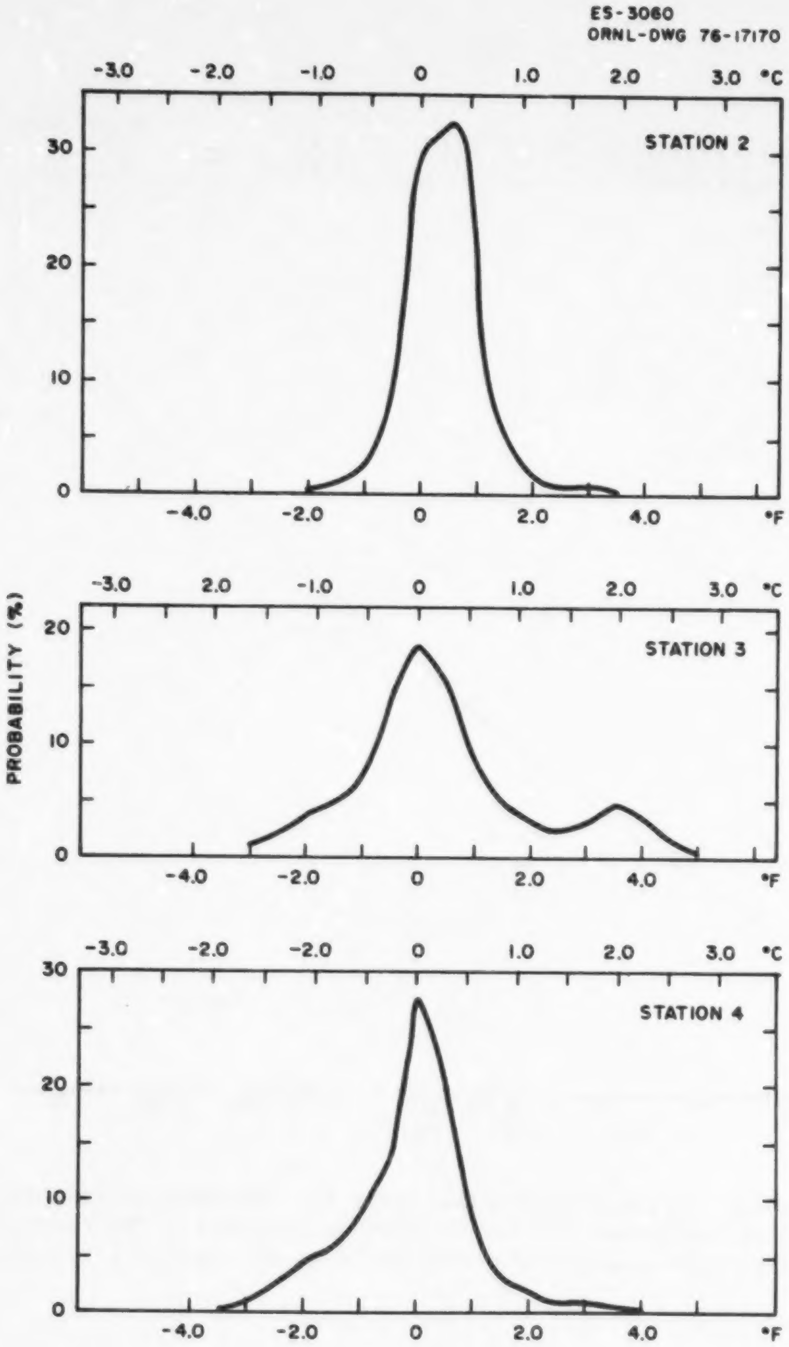

Fig. 9a. Probability vs excess temperature for stations 2 through 15.

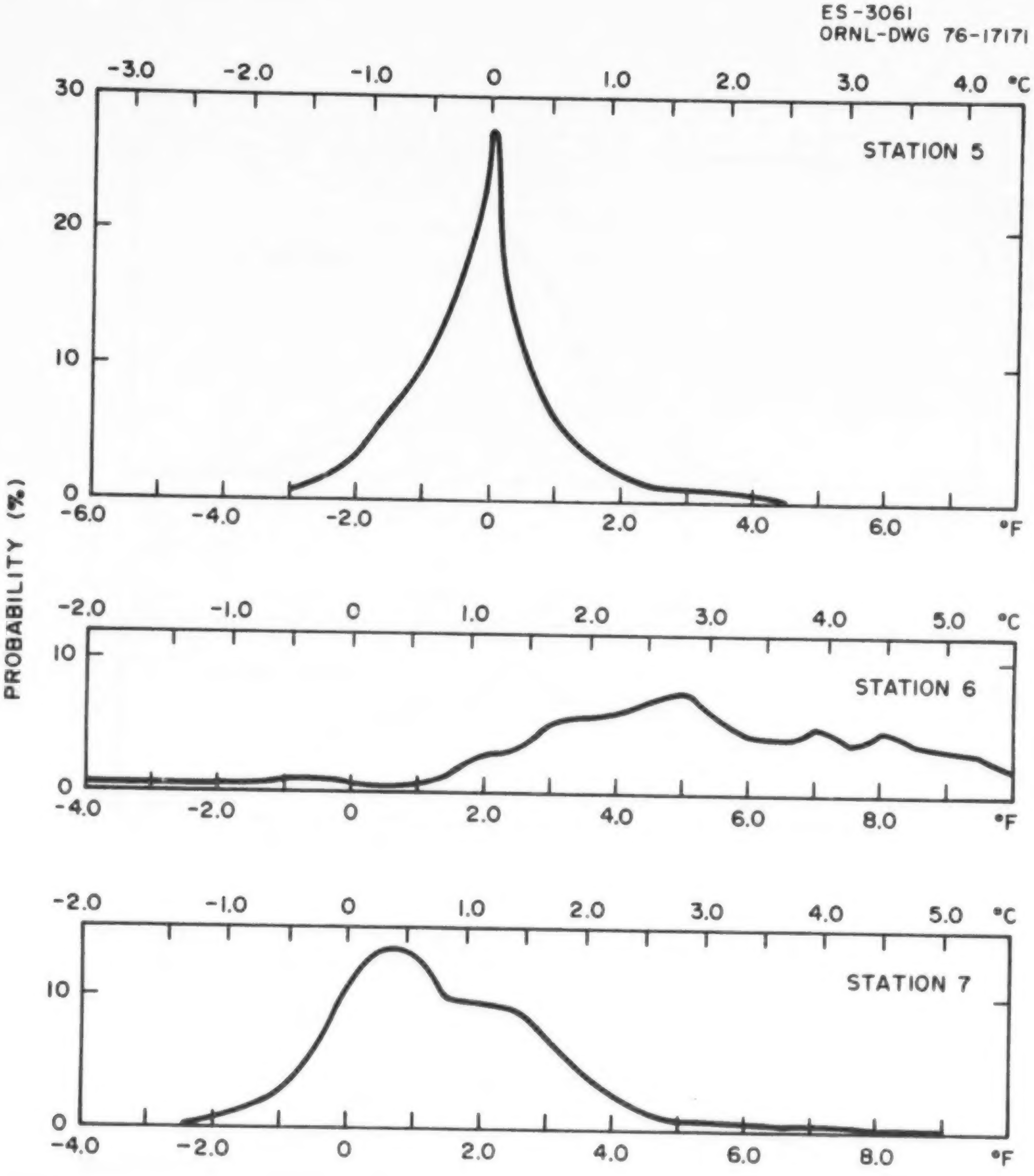
ES-3061
ORNL-DWG 76-17171
PROBABILITY (%)
STATION 5
30
20
10
0
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
°C
-6.0
-4.0
-2.0
0
2.0
4.0
6.0
°F
STATION 6
10
0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
5.0
°C
-4.0
-2.0
0
2.0
4.0
6.0
8.0
°F
STATION 7
10
0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
5.0
°C
-4.0
-2.0
0
2.0
4.0
6.0
8.0
°F

Fig. 9b

ES-3062
ORNL DWG 76-17172

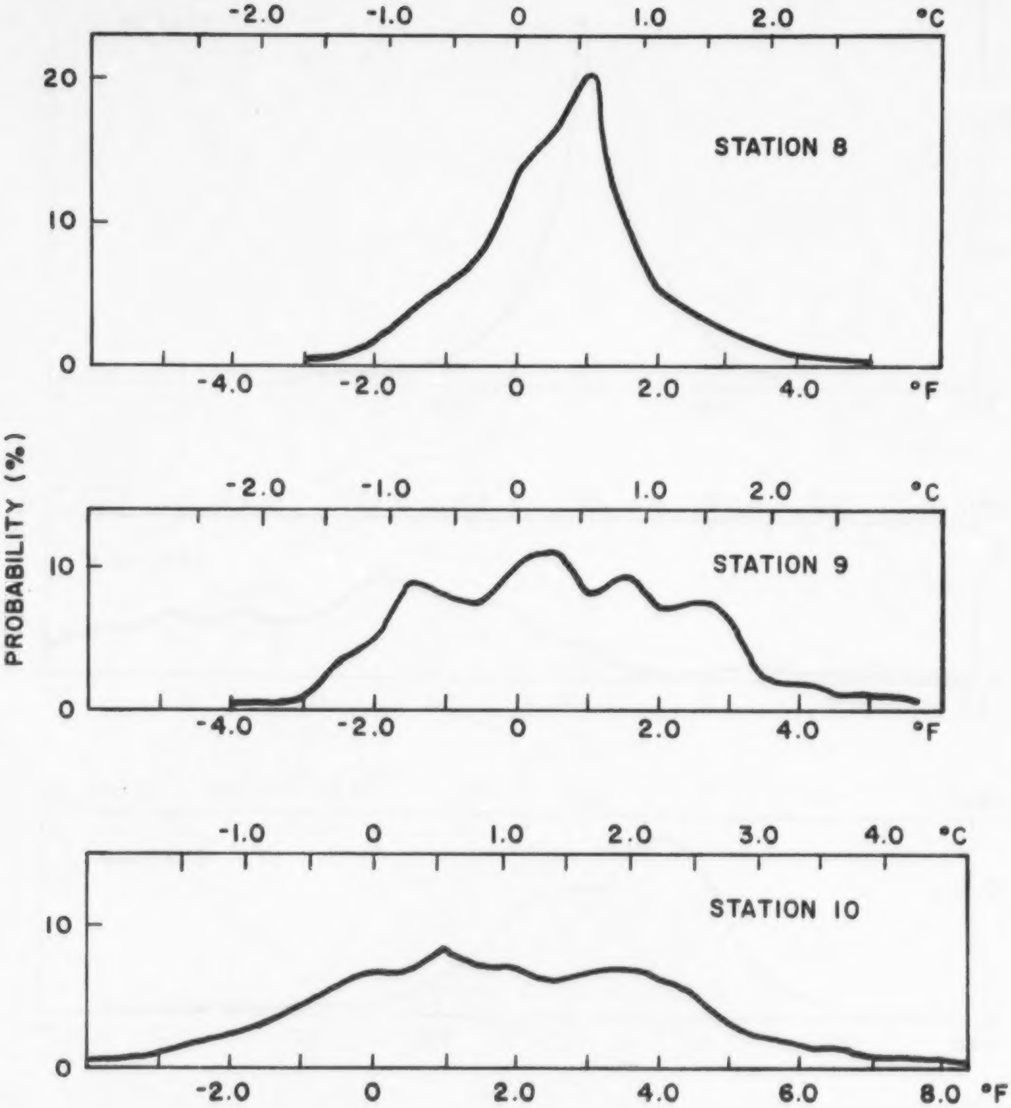

Fig. 9c

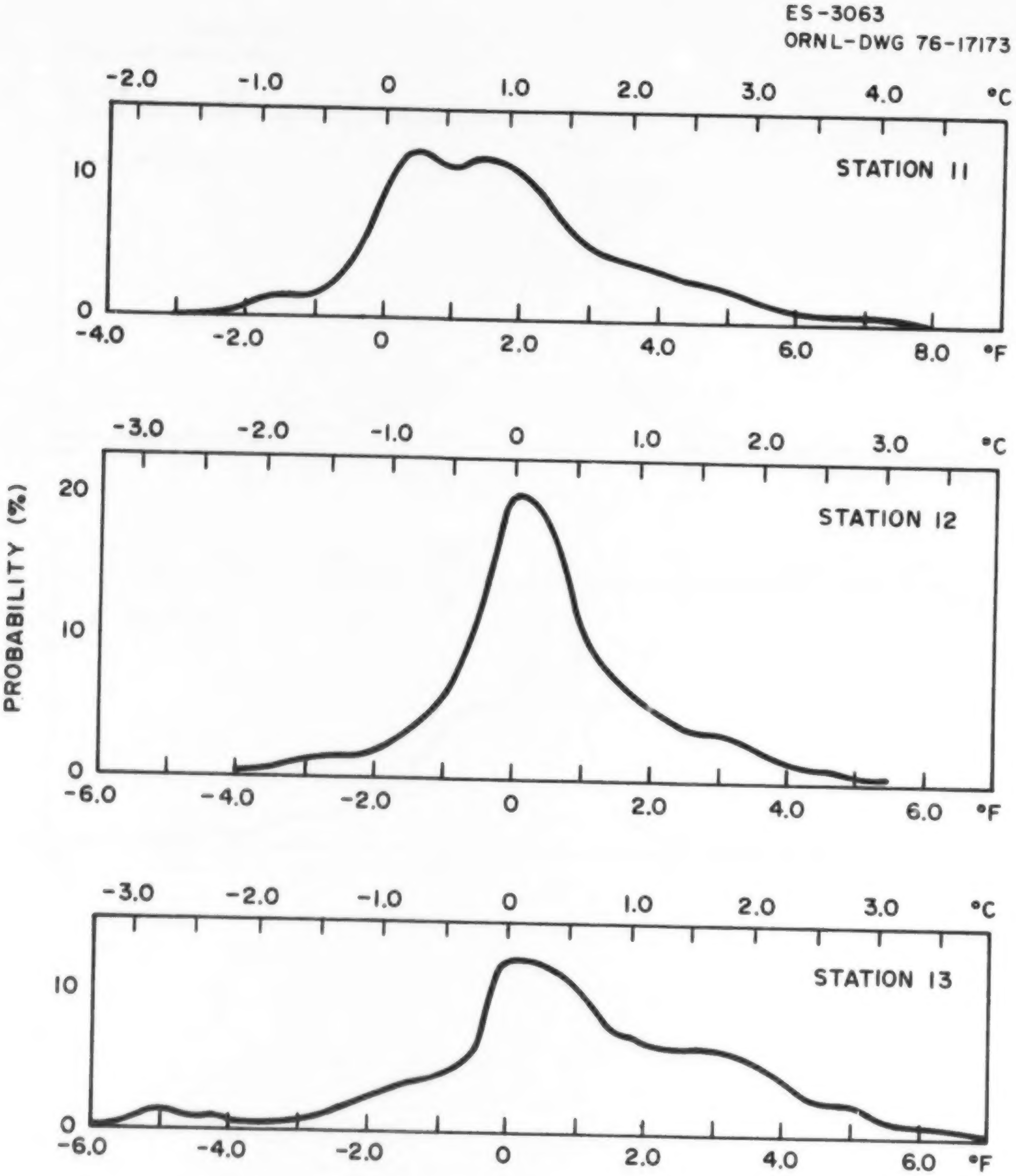
ES-3063
ORNL-DWG 76-17173
-2.0
-1.0
0
1.0
2.0
3.0
4.0
°C
10
0
STATION 11
-4.0
-2.0
0
2.0
4.0
6.0
8.0
°F
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
°C
20
10
0
PROBABILITY (%)
STATION 12
-6.0
-4.0
-2.0
0
2.0
4.0
6.0
°F
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
°C
10
0
STATION 13
-6.0
-4.0
-2.0
0
2.0
4.0
6.0
°F

Fig. 9d

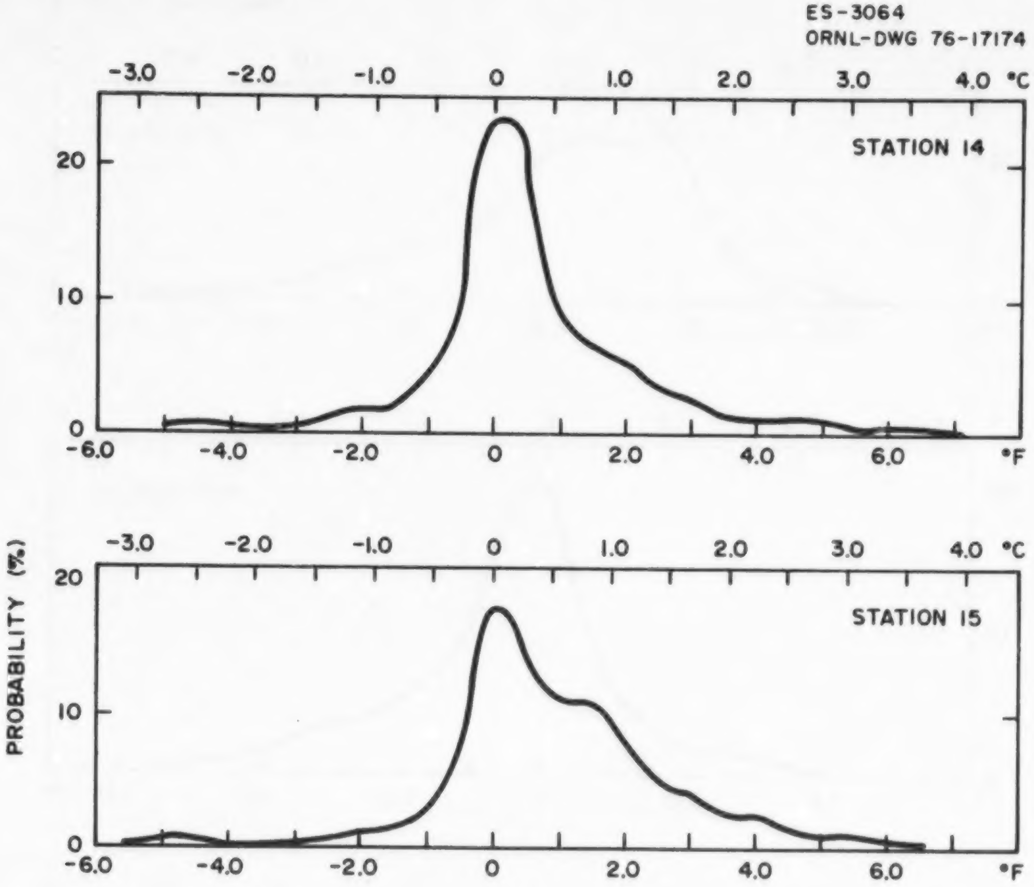

Fig. 9e

AJW
461<

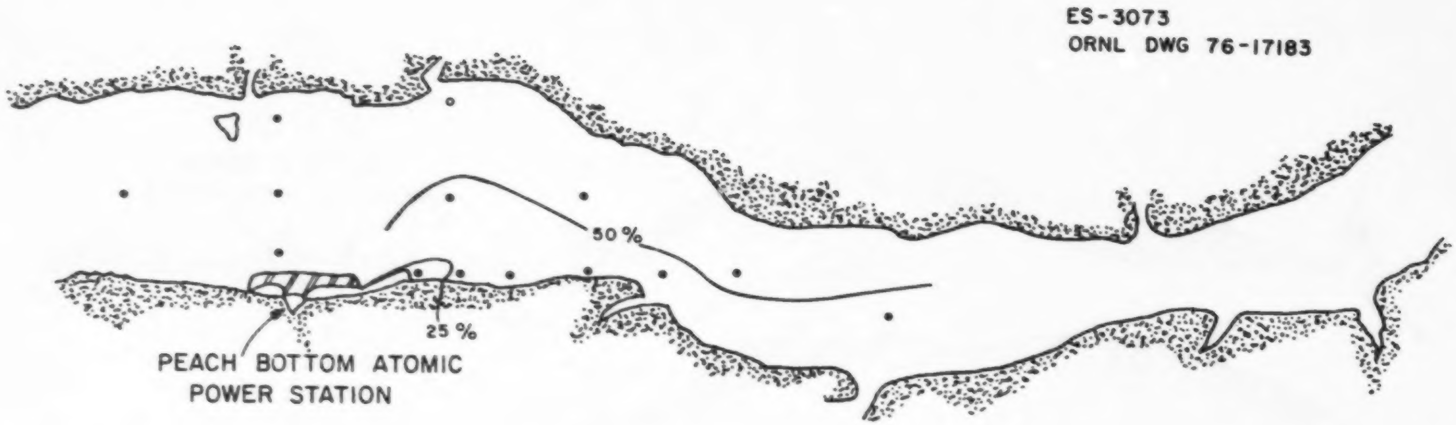
ES-3073
ORNL DWG 76-17183
50 %
25 %
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10a. Surface excess temperature extent contours for excess temperatures of (a) 0.5°F (0.28°C), (b) 1.0°F (0.6°C), (c) 2.0°F (1.1°C), (d) 3.0°F (1.7°C), (e) 5.0°F (2.8°C), and (f) 10.0°F (5.6°C).

ES-3074
ORNL DWG 76-17184

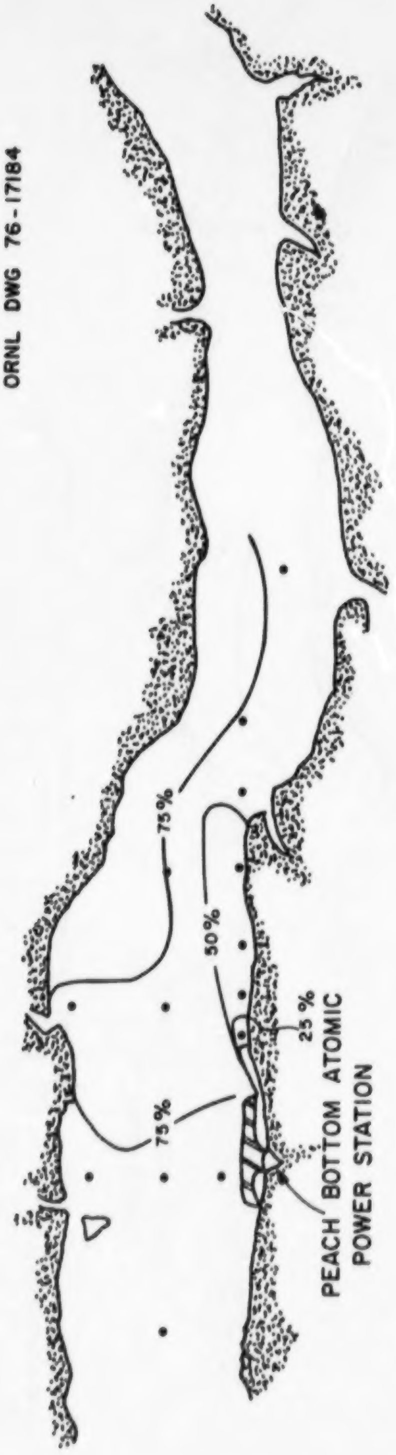
75%
50%
25%
75%
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10b

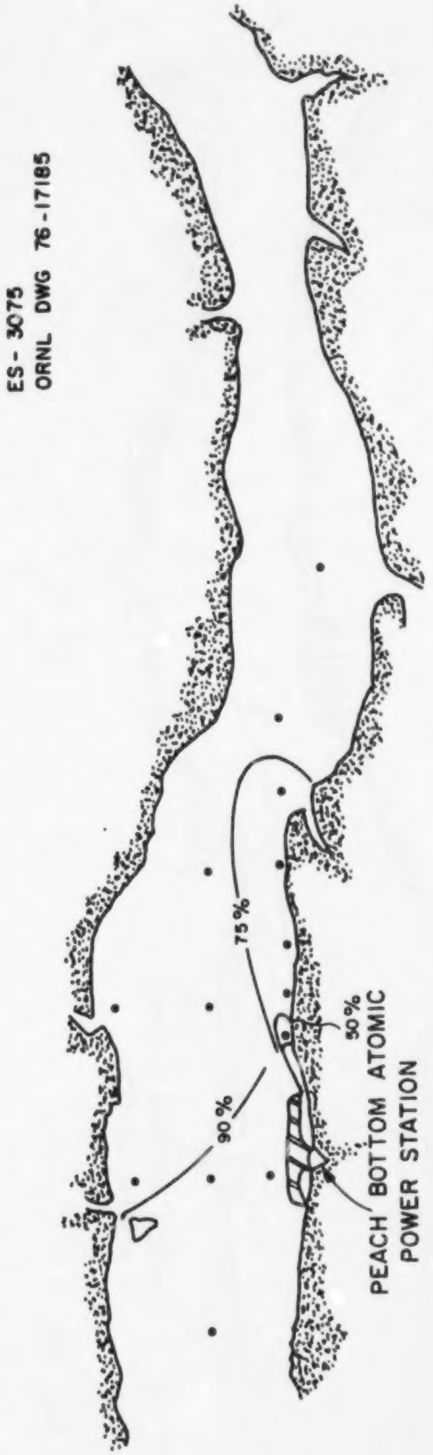
ES- 3075
ORNL DWG 76-17185
75%
90%
90%
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10c

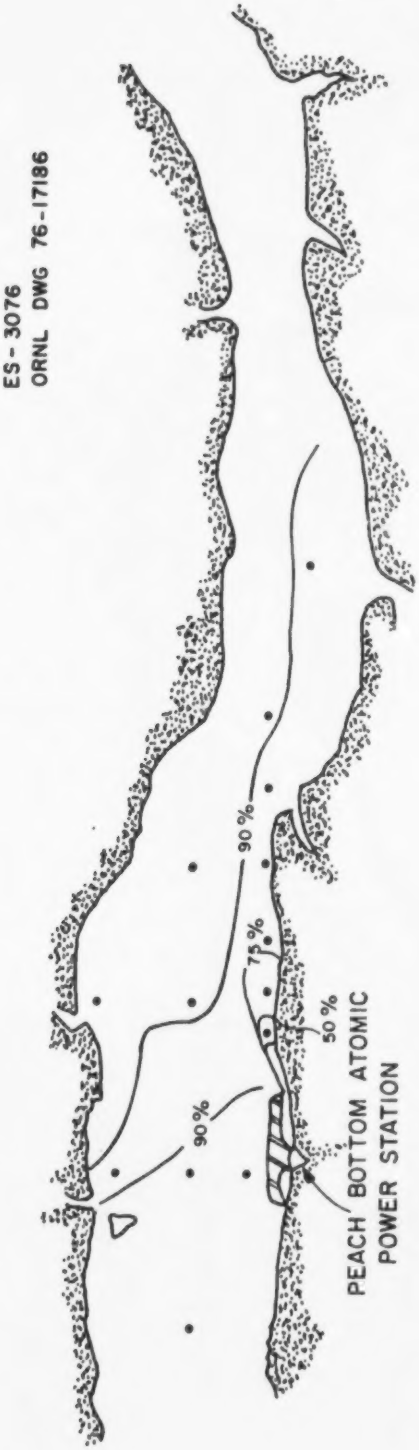
ES-3076
ORNL DWG 76-17186
90%
90%
75%
50%
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10d

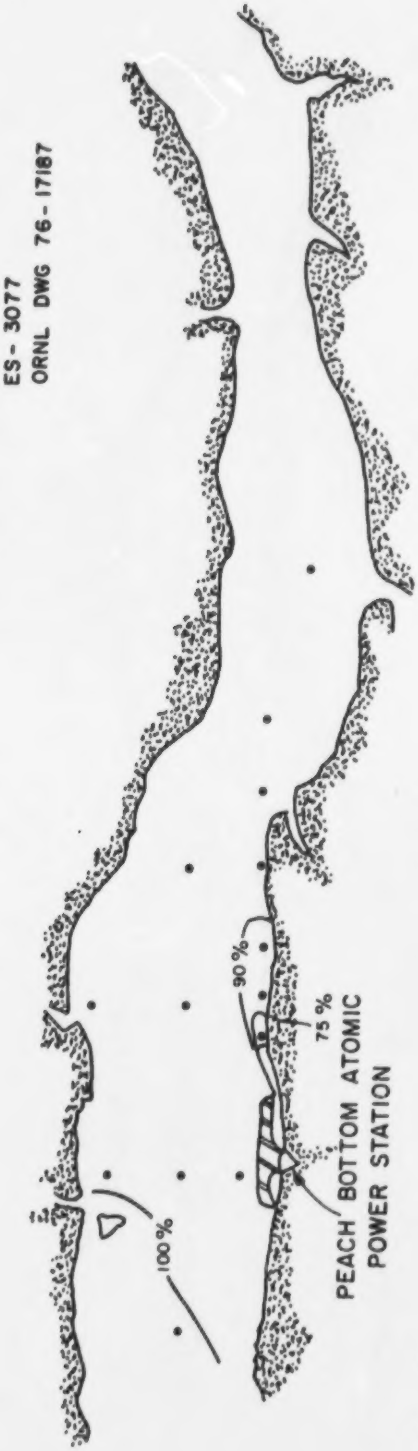
ES-3077
ORNL DWG 76-17187
90 %
75 %
100 %
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10e

AJW

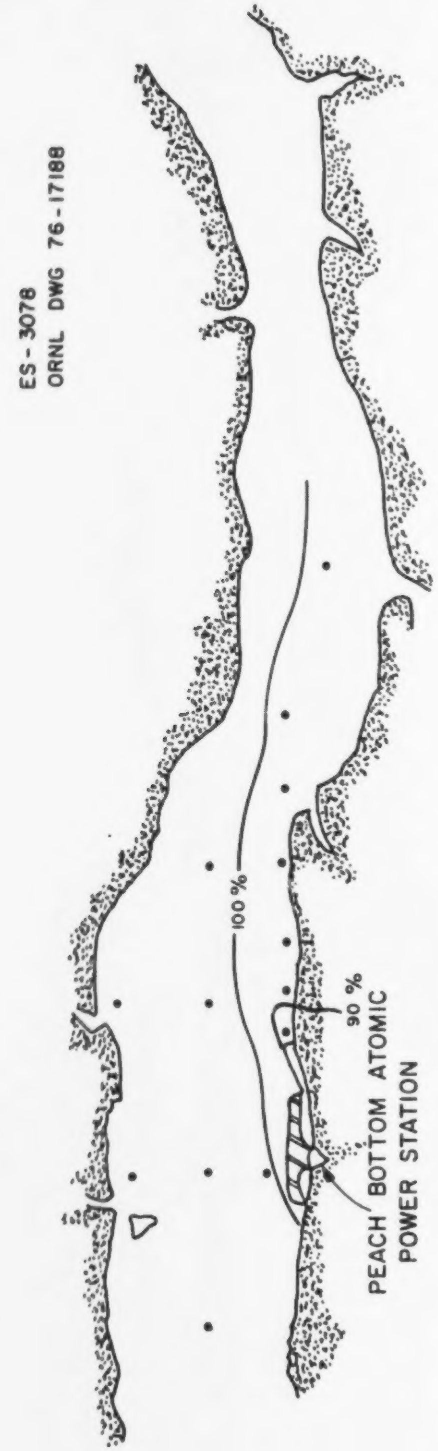
ES-3078
ORNL DWG 76-17188
100%
90%
PEACH BOTTOM ATOMIC
POWER STATION

Fig. 10f

omit

CONFERENCE ON WASTE HEAT MANAGEMENT AND UTILIZATION
MIAMI BEACH, FLORIDA X-B-103

Modelling the Influence of Thermal Effluents on Ecosystem Behaviour.

by Karl Iver Dahl-Madsen, The Water Quality Institute.

ABSTRACT

A necessary step in managing thermal effluents is calculation of biological/chemical consequences by means of a mathematical model. Different types of models can be used. And example of an empirical/statistical model which relates species composition to excess temperatures is given. Examples of the use of primary production models based on mass balances for phytoplankton and nutrients for calculating temperature effects on biomasses and roles of biological/chemical processes are shown.

Calculations of consequences of entrainment are carried through by means of a combined 2-dimensional transport-dispersion and zooplankton growth model. The results are presented as iso-concentrations of zooplankton.

Session X C

Monitoring

21-45-10

STATE OF THE ART OF THERMAL MONITORING PROGRAMS IN THE POWER INDUSTRY

J. Z. Reynolds
Consumers Power Company
Jackson, Michigan U.S.A.

ABSTRACT

Monitoring programs conducted for the purpose of demonstrating effects of once-through condenser cooling water systems must consider factors such as structural and hydrodynamic changes of intake and discharge areas, in addition to thermal changes. During the past few years, monitoring programs and special studies at many power plants have produced substantial amounts of new information that is useful in assessing actual and potential impacts on aquatic systems. At the same time, efforts such as the publication of the AIF-NESP "Source Book on Monitoring Methods" and the EPRI "Report of a Workshop on the Impact of Thermal Power Plant Cooling Systems on Aquatic Environments" have helped focus emphasis on the practical aspects of relating monitoring program design to measurable and potentially significant consequences from an ecological standpoint. Methods for studying effects on ecosystems in field monitoring programs are not sufficiently developed to clearly establish cause-effect relationships. In most cases, however, by appropriate characterization of waterbody types and relative assessments of impact, monitoring programs can supply adequate information to relate potential effects with prevailing decision criteria.

INTRODUCTION

In assessing the state of the art of thermal monitoring programs in the power industry (which will be largely limited here to aquatic monitoring related to once-through circulating water systems) it is useful to consider the historical context of current practices as compared to previous periods, and the prime factors that directly changed in these practices. In the mid-1960's the states were directed by the Federal government to establish water quality standards that would include limitations on temperature. The pressure to develop numerical limitations for temperature had the unfortunate effect of focusing regulatory (and scientific) concern on only this one aspect of circulating water system effects. In addition, the efforts to fit the peculiar characteristics of temperature changes in the same framework as conservative pollutants caused fundamental misconceptions as to even the nature of thermal effects. It is not surprising, therefore, that practically all the investigative monitoring efforts on cooling systems during this period were directed at defining thermal plume and heat dissipation characteristics, without much regard for biological or ecological significance.

The passage of NEPA in 1969 (which requires consideration of all environmental effects) and the 1972 Amendments to the Federal Water Pollution Control Act (which singles out thermal discharges and cooling water intake systems as requiring special consideration) have provided the means for a more balanced and thorough approach to monitoring effects of cooling systems. While the matter of temperature being defined as a "pollutant" (as it is in the 1972 Amendments) and the methods by which these laws and associated regulations have been administered are questionable, there is now legal recognition that the impacts are multi-faceted and must be considered in terms of ecological and resource management principles. The decision of the Fourth Circuit Court that remanded the thermal effluent limitations is seeking to have the regulations corrected in a manner that will properly state the benefits of thermal limitations to aquatic life or provide adequate scientific opinion to establish the potential benefits in relation to the monetary costs and other effects.[1]

The early biological studies of cooling system effects naturally exhibited a conventional, pollution investigator's approach to determining significance. Studies of benthic organisms had been used quite widely and successfully in documenting pollution effects on stream and lake ecology and it was assumed that these organisms would be appropriate indicators of thermal discharge effects. While not discounting the validity of this concept for identifying widespread effects, it became readily apparent that cooling water discharges were not causing changes that would be exhibited by conventional observations of indicator organisms. The thresholds of observable effects were not generally to be found at the ecosystem level, at least as a matter of initial observation.

Further investigation to identify possible water quality and biotic changes resulting from once-through cooling water use led to a realization that temperature effects were largely near-field phenomena and that habitat modification (due to structural and hydrodynamic changes) intake impingement and circulating water entrainment constituted more direct and observable impacts than any conceivable far-field temperature influence. It was thus that the pendulum swung the other direction, with regulatory (and scientific) concern for documenting individual effects in the intake and immediate discharge areas, without a clear perspective of how these effects could be related to larger scale concerns, such as ecological dependencies or resource management objectives.

ADVANCEMENT OF MONITORING TECHNIQUES

The requirements for rapid expansion of aquatic monitoring programs at power plants throughout the country preceded any opportunity to assess the state of the art of monitoring techniques on a broadly coordinated basis. The techniques utilized in most sampling programs were established based on individual investigator preferences or pragmatic factors, such as availability of equipment and practical field situations. Monitoring program designs have usually been established through negotiations between utility representatives, consultants, academicians and regulators and, at best, represent a compromise between everyone's best guesses as to what would most appropriately satisfy their aims. Sampling methods alone have been nearly as varied and diverse as the habitats studied, and comparatively few sampling approaches have been applied routinely.

While this type of uncoordinated and ill-defined approach might seem wasteful and unproductive, it has resulted in the testing of a great many approaches to monitoring situations. And, while in retrospect the results of many of these programs are of questionable scientific value, we do have confidence now as to which techniques and program design approaches are preferred under many different circumstances. In addition, in spite of the multitude of approaches, investigators have been largely unsuccessful in uncovering instances of ecological harm or large-scale damage to aquatic resources as a result of once-through cooling systems. The significance of this can be emphasized in view of the fact that most of these programs have been directed toward observations of preconceived adverse effects, instead of toward balanced and unbiased documentation of effects that would give credit to potentially beneficial changes.

There was clearly a need for a coordinated evaluation of monitoring methods which would consider, in an objective way, the state of the art of monitoring technology for all types of environmental impact. In 1973, the Atomic Industrial Forum, NESP Project contracted with Battelle Pacific Northwest Laboratories and Columbus Laboratories to provide such an evaluation and to publish a guide to state of the art techniques presently available to monitor environmental impacts of nuclear power plants.

This guide was published in February 1975[2] and includes sections on specific methods, equipment and procedures most likely to satisfy the requirements of Section 6 of the AEC Regulatory Guide 4.2, March 1973 (which has now been updated as NRC Regulatory Guide 4.2, Rev. 2, July 1976). The section on aquatic ecology is the most comprehensive and up-to-date source of information available on thermal monitoring program techniques. The subjects cover basic considerations of all phases of monitoring, ranging from design aspects of collecting gear, sample handling and analysis to making biomass and productivity estimates, measuring physiological and behavioral responses, observing abnormalities, and computing indicators of biological response and statistical significance.

Comments on sampling techniques are provided regarding applicability and known or suspected limitations of use from both a quantitative and qualitative standpoint. Methodology for processing samples is discussed and extensive references are provided for detailed information on preservation, preparation, sorting, identification and analysis of organisms. Laboratory and bioassay techniques are described in considerable detail, particularly with regard to the increasing emphasis on assessing chronic and sublethal effects. The problems of relating thermal effects as observed in the laboratory to field situations are discussed in terms of behavioral and physiological responses.

The monitoring rationale stresses that programs should be developed individually for each site and consider the peculiar requirements of initial site studies (to identify possible impacts and predict extent of expected changes) preoperational or baseline studies (to quantify characteristics of ecosystems before operation) and operational monitoring (to measure plant effluents and ecosystem changes in the vicinity of the plant).

The rationale states further that: "Comparison of data collected during the preoperational and operational programs forms the basis for determining impacts caused by plant operation. Hence, any monitoring program must be of sufficient scope to account for natural variability of ecosystems at the plant site to properly attribute observed changes to either natural conditions or plant operation."[2]

Herein lies the basic problem with all such monitoring programs. Aquatic organisms and populations react to their total environment and to many antecedent conditions rather than single factors. It is virtually impossible on a prototype scale to measure and adequately integrate all physical, chemical and biological factors that will influence the ecosystem. It is therefore imperative that monitoring programs concentrate on key parameters that will provide reasonably valid indications of significant impacts, with appropriate consideration of natural variability.

The "representative, important species" approach adopted by EPA[3] does recognize the practical impossibility and futility of total ecosystem study as a means of fulfilling the statutory directive of Section 316(a) of PL 92-500 to protect the "balanced, indigenous population" or community of aquatic organisms. It falls far short, however, of providing a rational framework for design of monitoring programs that will provide results that can, in turn, be reasonably translated to decisions regarding the environmental significance of effects.

In addition, the regulations leave to the discretion of the permitting authority the decision as to whether or not the selected species approach is adequate to provide assurance of community protection.[3]

MONITORING FOR ECOLOGICAL SIGNIFICANCE

The aquatic monitoring and research programs being sponsored by the electric utility industry constitute, collectively, probably the most extensive ecological study effort in history. It is very questionable, however, whether this effort has indeed advanced the state of the art and whether the findings of these programs have served as a rational basis for regulatory decisions that have been made regarding environmental significance of cooling system effects.

The Electric Power Research Institute sponsored a workshop in the Fall of 1975 on the impact of thermal power plant cooling systems on aquatic environments, which I was privileged to attend. While the primary purpose of the workshop was to develop priorities for future research, the outcome was inevitably linked to an assessment of the results of prior monitoring and research and perceptions of what "issues" would emerge as significant in terms of regulatory interest and/or ecological importance. Proceedings of this workshop were published by EPRI and contained topical presentations by the participants as well as results of group discussions.[4]

While the relationship of ecological monitoring results to regulatory decision criteria was not specifically a topic of the workshop, this important consideration was reflected in many comments and is discussed further below.

It was generally agreed by the participants that the major challenge at the present time lies in relating increments of direct biological change seen at the individual organism level (e.g., lethality or changes in such responses as growth, fecundity or behavior) to responses on populations, communities and ecosystems. At the present level of sophistication, the question of monitoring techniques and needs for improvement received a relatively low priority.

It was conceded, however, that much biological sampling has never been subjected to critical examination for performance consistency under different sampling conditions, and that as research progresses on impacts on organism behavior, populations, communities and ecosystems new research and monitoring equipment needs will require development.[4]

Most important at the present time is the need to develop adequate analytical methods which are suited to expanding the scope of quantitative predictions. Prominent areas of inquiry in this regard are population dynamics theory and modeling techniques, identification of discrete stocks of species in question, and delineation of mortality rates for various life history stages.[4] Understanding of the relationships between water movement, in both intake and discharge areas, and biological activity is obviously important in terms of predicting impact and relating monitoring results to plant design and operation.

It should always be anticipated that behavioral and/or physiological responses of organisms on a measurable scale may occur as a result of totally unforeseeable phenomena. Investigators should have the flexibility in a comprehensive monitoring program to weigh the importance of such observations on a short-term basis and, within the resources available, conduct systematic studies to identify the causes of observed responses. The ability to do this will not only result in a better coupling of monitoring results with predictions of plant effects, but may help define natural controlling factors that influence organism behavior and populations.

To follow this approach to its extreme and to attempt to completely characterize the variability of ecosystems is not necessary or, except in the case of relatively small and simple systems, possible. Zones of relatively high biological importance, however, such as migration routes and spawning areas, can be reasonably well defined within the context of potential plant effects. Monitoring efforts, to be most productive, should thus concentrate on those areas where there is some threshold showing of potentially significant change and on those variables that are likely to show some correlation with biological changes, either natural or induced. Further concentration of investigative efforts on extreme conditions and at plants that represent worst case conditions would be most productive in establishing thresholds of significance as a guide to monitoring requirements at other plants. The generic research efforts sponsored by EPRI on categorization of cooling water effects by waterbody type should contribute significantly to this goal.

MONITORING AS A RESPONSE TO REGULATORY CONCERNS

As suggested previously, existing monitoring programs have been developed to be primarily responsive to regulatory concerns instead of for ecological significance. Regulatory guidelines[5,6,7,8] in this area have had the unfortunate effect of producing voluminous amounts of monitoring data of questionable interpretive value. Some of these guidelines, even in draft form, have the effect of regulation, but inherent inconsistencies and the impractical nature of many questions they raise offer, in effect, little guidance for proper focus of effort in a monitoring program.

Industry comments on the EPA draft guidance manuals for 316(a) and 316(b) studies and NRC Regulatory Guide 4.8 have been widely distributed and include many specific points with regard to deficiencies of these documents as they relate to monitoring programs. In general terms the most serious deficiencies in this regard are:

1. In spite of a tacit recognition that environmental effects and related programs are site specific, they leave little flexibility to tailor study programs to individual sites.

2. While emphasizing that the environmental significance of impacts must be established, there is little recognition of the relative context in which such impacts may be assessed. The decision criteria are invariably expressed in subjective, preservationist terms and are unrelated to resource management considerations.

3. There is little recognition of cost-effectiveness and practical, as well as state of the art, limitations of producing monitoring data in a manner consistent with program objectives or decision criteria.

These types of deficiencies in a regulatory guidance document practically insure that disputes will arise with respect to monitoring program design and interpretation of results. Unfortunately, the most likely outcome of such disputes is that conservatism will be built into future designs for the purpose of simplifying the resolution of issues that are expected might arise. This course of action is almost certain to stifle initiative in plant design and consideration of alternatives that might be directed at resource improvement. The resultant effect may cause increased environmental damage and cost, without the desired balancing of reasonable alternatives.

The 316(a) draft Manual of EPA identifies six "biotic categories" (phytoplankton, zooplankton, habitat farmers, shellfish/macroinvertebrates, fish and other vertebrate wildlife) and requires successful demonstration as to all categories, even for "second round" demonstrations.[5] Because of the presumption that unacceptable impacts may occur in any category at any future time, in spite of a prior successful demonstration, it appears that monitoring programs may require increasing refinement to establish precise levels at which plant induced changes are no longer statistically observable in all biotic categories, without much regard for biological significance. Although the decision criteria are expressed in subjective terms, there is considerable concern that the level of precision required by the regulatory agencies may be impossible to achieve.

The 316(b) draft Manual of EPA went beyond the subjective decision criteria in the 316(a) Manual for determining environmental significance. In doing so, however, there is increased emphasis on quantitative precision, statistical reliability, and frequency of sampling that goes beyond what is reasonably necessary for the "best technology" decision.

As pointed out in industry comments, even in those cases where quantitative precision is needed, specific rules that would require sampling at certain intervals are inappropriate. Seasonal phenomena, such as fish impingement and larvae abundance, may be adequately documented with a flexible program that allows for increased intensity of effort during critical periods, if the basic program is adequate to characterize magnitudes and reveal when thesholds of change are occurring.

The need for demonstrating statistical significance in the various aspects of a monitoring or study program should be carefully considered in terms of practical limitations and how the results may be related to biological significance. The 316(b) Manual indicates that the most variable of the representative, important species of ichthyoplankton under study at a given season will determine the number of replicates necessary, and that confidence limits for population estimates must be sufficiently narrow to insure that real and significant differences are detectable.[6] It is questionable whether statistically reliable population estimates can be made even for the most abundant species. However, to gear the sampling program to the most variable of the species under consideration could easily lead to the need for an unlimited number of replicates to quantify a condition that, because of the generally sparce but highly variable occurrence of the species, has little biological significance.

The recent decision of the EPA Region I Administrator in the Seabrook Case in New Hampshire is evidence that state of the art limitations in monitoring techniques and evaluation may, in essence, be used as a principle factor for deciding that impacts will be unacceptable. His statement "that the impact of Seabrook Station on a highly dynamic ecosystem is difficult, if not impossible, to predict, although it is clear that there will be an effect" if allowed to stand as a basis for his decision, is fair warning that no utility will be allowed to proceed in the face of a contrary regulatory opinion, even if the weight of evidence regarding environmental requirements may be favorable.[9]

EPA has also taken the position in the case of the Brunswick Nuclear Power Station in North Carolina that the inability to directly measure and know the effect of organism loss on population levels requires that cooling towers be built. They further argued that direct measurement of populations, let alone impacts from various sources on those populations, is not now possible within the existing state of the art and probably cannot be accomplished in an estuarine situation in under 10 to 100 years.[10]

There is no end to the number of questions a knowledgeable person can raise about impact assessments and the adequacy of related monitoring programs. Theoretically, a highly dynamic ecosystem is more capable of assimilating and adjusting to environmental changes than one characterized by more stable conditions. The added complexities of a highly dynamic or diverse ecosystem, however, are most suited to in-depth questioning, so the tendency may be to avoid such areas and locate plants where the impacts on the aquatic system can be more confidently identified or in some manner directly measured, even though the net environmental impact may be greater.

Quantitative precision and statistical reliability, while the goal of all researchers, must be weighed in terms of the decision criteria to be applied. The 316(b) Manual, with some caveats, would require quantitative estimates of fish populations by extensive, long term field studies. Such quantitative estimates are not normally necessary to establish thresholds of significance, when comparison of data on historic catch, sampling results, range of known habitat, and accepted cropping information can provide an adequate basis for establishing whether or not adverse effects may occur. In addition, prior to requiring extensive studies, there should be some consideration of whether or not any reasonably postulated adverse impact, if found to be significant, can be remedied by feasible measures. Detailed monitoring and investigation to document effects where remedial changes are known to be completely infeasible should not be required. There may be reasons, such as for research or application to other circumstances, where such information would be worthy of collection; however, the purpose should be explicitly defined and not required as a matter of routine.

CLOSURE

There has been considerable conflict between and among scientific, regulatory and utility interests regarding thermal monitoring program requirements. Unlike the situation in the mid-1960's when regulatory interest in temperature limitations began, the state of the art of monitoring techniques is well documented. A large gap remains, however, in the philosophy of approach in designing monitoring programs to adequately accommodate diverse concerns for protection and utilization or management of aquatic resources.

From a scientific viewpoint, efforts must be encouraged to develop threshold levels of concern on a realistic basis so that monitoring resources can be efficiently applied, instead of being wasted in random data gathering activities. This can be done by appropriate characterization of waterbody types and relative assessments in terms of scale of impact. The EPRI program has several projects underway that are designed to develop this characterization and will, hopefully, establish thresholds of significance for cooling water use.

Assuming these and similar efforts are reasonably successful, the problems will remain of incorporating the results into the regulatory process to further resource management objectives and to further demonstrate that unacceptable adverse effects are not occurring.

Monitoring program results can theoretically provide useful information for resource management programs if suitably designed for this purpose. If certain species are killed or, on the other hand, their growth or activity modified, desired species may be reintroduced or otherwise managed to compensate for changes considered to be undesirable. To do this in practice would stretch the level of credibility regulatory agencies have been accustomed to giving such data, but such information could serve to help redirect efforts that might be spent on correcting vaguely defined problems to actually improving the resource.

On-site biomonitoring of captive organisms provides, in many cases, a suitable link between laboratory and field conditions for identifying sublethal stresses and other abnormalities and it is anticipated increased recognition will be given to such methods using mixed species, as well as indicator or target species. Biomonitoring has an additional advantage in that it can provide visual evidence to those concerned that an effluent is not harmful to aquatic life.

Final proof of environmental effects, however, requires monitoring of actual field conditions, and it is certain that such programs at some level will be a requirement of all major users for the foreseeable future.

An American National Standard for Aquatic Ecological Surveys Required for the Siting, Design, Construction and Operation of Thermal Power Plants is under development which suggests some general principles for fulfilling aquatic ecological information needs.[11] The first principle is the recognition of limitations inherent in the current biological state of the art. The fact that aquatic ecology is not generally a predictive science is a controlling limitation and it is clearly indicated that the status of biological knowledge for relating natural variability to man-induced changes and resource management considerations should be important factors in survey design.

Other principles stress the need for careful consideration of aquatic information needs in relation to specific plant and site considerations and the potential utility of the data obtained. The value of uniformity in design, conduct and analysis of aquatic ecological surveys is also discussed.

The proposed standard further suggests, in matrix form, information needs (by source, frequency, relative spatial distribution and detail of biotic information) for different cooling water systems, types of aquatic habitat and stages of plant development. It is stated, however, in accordance with the principles identified, that the standard is intended as an aid to, not as a substitute for, professional judgment on a case-by-case basis. Other guidelines for thermal monitoring programs would do well to incorporate principles that give full recognition to state of the art limitations of aquatic ecology and other practical aspects relating to study and management of aquatic resources.

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EVALUATION OF ENVIRONMENTAL IMPACT PREDICTIONS[a]

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EVALUATION OF ENVIRONMENTAL IMPACT PREDICTIONS

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ABSTRACT

An analysis and evaluation of the ecological monitoring program at the Surry nuclear power plant showed that predictions of potential environmental impact made in the Final Environmental Statement (FES), which were based on generally accepted ecological principles, were not completely substantiated by environmental monitoring data. The Surry nuclear power plant (Units 1 and 2) was chosen for study because of the facility's relatively continuous operating history and the availability of environmental data adequate for analysis. Preoperational and operational fish monitoring data were used to assess the validity of the FES prediction that fish would congregate in the thermal plume during winter months and would avoid the plume during summer months. Analysis of monitoring data showed that fish catch per unit effort (CPE) was generally high in the thermal plume during winter months; however, the highest fish catches occurred in the plume during the summer. Possible explanations for differences between the FES prediction and results observed in analysis of monitoring data are discussed, and general recommendations are outlined for improving impact assessment predictions.

INTRODUCTION

Appendix B of the operating license of each nuclear power plant contains specific requirements for environmental surveillance including both radiological and nonradiological monitoring. These requirements, known as Environmental Technical Specifications (ETS), contain provisions for monitoring power plant operations to assure that environmental conditions actually exist as stated in environmental impact statements, and that operating conditions and impacts on the environment are maintained within specified limits. A critical evaluation of the nonradiological Environmental Technical Specifications program was performed using data collected at several operating nuclear facilities, and results are reported in Adams et al. (1977) [1,2,3,4]. These authors sought to determine whether (1) individual environmental monitoring programs conformed to the intent of the Appendix B Requirements; (2) whether monitoring programs were adequate to detect environmental impacts that were predicted; (3) whether a significant impact had occurred after the power plant became operational; and (4) whether the Technical Specifications needed to be revised in light of recent advances in impact analysis and environmental monitoring. Many common problems associated with environmental impact analysis were identified in that study which examined nuclear facilities located in an East coast estuary, a freshwater impoundment, and a Pacific coastal marine environment.

In this paper, analysis of five years of environmental monitoring data collected at the Surry power plant is presented to illustrate the procedure we employed in evaluating the validity of Final Environmental Statement (FES) predictions of environmental impact. The Surry nuclear power plant was selected for study based on the plant's relatively continuous operating history and the availability of the environmental monitoring data collected during both the three preoperational years and two operational years. Particular emphasis in this study was directed toward assessing the validity of the FES prediction which stated that "during the summer, fish may avoid the discharge (thermal plume) area; however during the winter, fish may congregate in the thermal plume" [5,6]. If fish congregate in the plume during the winter months, fish kills due to cold shock could potentially result if the plant were forced to shut down the reactors abruptly. Using five years of fish-trawl data (collected as part of the Environmental Technical Specifications), the validity of the prediction was evaluated. In order to assess the validity of this impact prediction, it was first necessary to identify the horizontal and vertical extent of the thermal plume, then to identify those monitoring areas receiving maximum exposure to the thermal plume as well as comparable monitoring areas not influenced by thermal elevation (control area) and, finally, to compare results of the fish monitoring program with the FES prediction.

THERMAL PLUME ANALYSIS

The Surry Power Station (Units 1 and 2) is located on the James River estuary (centered at Hog Point) 30 miles upriver from Chesapeake Bay and 55 miles downriver of Richmond, Virginia. Surry Unit 1 began commercial operation in December 1972, while Unit 2 began operation in May 1973 [7]. Condenser waste heat from both units is dissipated by once-through cooling. Cooling water is withdrawn from the James River on the downriver side of Hog Point through a 5000-ft long surface canal (Fig. 1). Thermal effluent water (ΔT = 14°F, 7.8°C) is discharged on the upriver side of the peninsula through a 2900-ft long surface-discharge canal [2]. The ΔT values at the discharge varied with plant operation and seasonal variations occurred in the ambient (intake) and discharge water temperature (Fig. 2) [7].

The James River at Hog Point can be characterized as a tidal estuary with salinity fluctuations (ranging from 0-18 o/oo) occurring in a regular cycle. Because the intake is located downstream of the discharge, intake water can be of a higher salinity than ambient water at the discharge, causing the thermal plume to sink to the bottom under certain conditions. An example of the three-dimensional extent of excess temperature off the Surry discharge (constructed from hydrothermal data collected in a moving boat survey) is presented in Fig. 3. It should be noted that this delineation of the extent of the thermal plume was conducted during a low slack tide period when both Units 1 and 2 were operating at nearly maximum capacity and thus may represent the maximum extent of the Surry thermal plume in the river.

Vertical thermal profiles of transects T_4 and T_5 which traverse the discharge area show that the plume (as defined by 7.2°F, 4°C excess temperature) extends to the bottom in the shallow inshore areas directly off the Surry discharge. This is the area in which trawl transects DA, DB, and DC are located (Fig. 1). Vertical profiles of transects T_1, T_3, and T_6 which correspond to fish trawl transects INT, HPS-N, and JI respectively, are characterized by the presence of little or no excess temperature rise (Fig. 3). These transects were thus designated as controls. An extensive study of all hydrothermal data collected at Surry was conducted using probability distribution analysis, and the results support the selection of trawl transects DA, DB, and DC as discharge areas and transects INT, HPS-N, and JI as controls [2].

SAMPLING PROCEDURES

Fish sampling was conducted monthly at the six trawl transects in the James River using a 5.5 m × 3.05 m otter trawl with 6.4-mm bar mesh. At all transects, trawls were made perpendicular to the shoreline. In the plume area, three transects were made radiating off the discharge groin DA, DB, and DC while the control transects HPS-N, INT, and JI were located both upstream and downstream of the discharge in areas receiving only minimal thermal influence. All fish-catch data included enumeration and identification of fish species captured during a 10-min trawl at constant speed. Results are presented as the fish catch per unit effort (CPE).

Trawl data are available for three preoperational years (1971-1973) and two operational years (1974-1975) [7,8]. Assignment of 1973 as a preoperational year was made because thermal additions to the discharge area were minimal from January until June, after which time more consistent ΔTs were observed (Fig. 2). During 1971 and 1972, several monthly trawl surveys were not performed, and every station was not sampled consistently each month. From 1973 through 1975, however, trawl data were collected more consistently at the six transects.

RESULTS OF FISH MONITORING

Temporal variations in the monthly fish CPE occurred during both the preoperational and operational years in the discharge and control area (Fig. 4). Prior to plant operation (1971-1973), fish CPE in control areas generally exhibited peaks in spring and fall: April and October (1971), March and October (1972), and June and November (1973). After start-up, control fish catches were highest in January and December (1974), and January, April, and December (1975). This pattern, which is inconsistent with that of preoperational years, may be related to shifts in distribution of fish in the vicinity of the plant. In the discharge area, the preoperational fish CPE was lower during all months than the CPE in control areas with the exception of the months of December 1971 and October 1972; however, after start-up, discharge area fish catches were generally higher than control catches from March 1974 through December 1975. During the last six months of 1974, however, a period when both Units 1 and 2 were gradually shut down, discharge fish catches were comparable to control catches. Both Units 1 and 2 began operating at higher capacity during 1975, which may account for the large CPE observed in the discharge area during all months. In addition, discharge area fish CPE exhibited the highest peaks during the summer (May through October) contrary to the FES prediction. It was during this summer period that mean water temperatures measured at the end of the discharge canal averaged 95°F (35°C) or greater (Fig. 2). During 1975, the high CPE at the discharge during both summer and winter months seems to reflect preference of fish for the thermal plume area.

ANALYSIS OF FISH MONITORING DATA

In addition to the increased CPE in the discharge observed during the summer months of 1975, a definite increase in the annual fish catch for all discharge transects occurred during the transition from the preoperational to the operational period (Table 1). The ratios of the mean CPE in the operational years (O) to the mean CPE in the preoperational years (P) varied from 0.7 to 1.0 for controls and from 1.7 to 3.0 for the discharge transects, thus forming two distinct groups. The three control transects and three discharge transects were therefore combined to form a control and thermally stressed area (Table 2). In order to evaluate whether significant changes had occurred from the preoperational through the operational period, the ratios of the CPE were compared for the discharge and control area transects. The mean CPE was assumed to follow a Poisson distribution with a rate λ_t at time t. A square root transformation of the data was then performed using the method of Freeman and Tukey (1950) [9]. The ratio of the transformed mean CPE in the discharge ($\overline{X}$) to the transformed mean CPE in the control ($\overline{Y}$) is defined as follows:

$$\theta = \frac{\overline{X}}{\overline{Y}} ,$$

where

$$\overline{X} = \frac{1}{n}\sum X_i = \frac{1}{n}\sum\left[0.5\left(\sqrt{D_i} + \sqrt{D_i + 1}\right)\right]$$

= mean transformed CPE at the discharge ,

$$\overline{Y} = \frac{1}{n}\sum Y_i = \frac{1}{n}\sum\left[0.5\left(\sqrt{C_i} + \sqrt{C_i + 1}\right)\right]$$

= mean transformed CPE at the control ,

where D_i and C_i are the number of fish in the ith catch in the discharge and control respectively. Assuming the transformed CPE follows a normal distribution, the confidence intervals can then be calculated (Kendall and Stuart 1975) [10]. In Fig. 5, the ratios are plotted with the 95% confidence interval for each year. The ratio θ shows an upward trend. From 1971 through 1974, the confidence interval includes the θ value of 1, indicating that the mean CPEs in the discharge and control areas are not significantly different. In 1975, the interval does not include 1, indicating a significantly larger CPE in the discharge area. In addition, the mean CPE in the discharge increased directly as the mean annual ΔT increased (Fig. 5). The annual ΔT value in Fig. 5 was calculated by averaging water temperatures collected at several areas in the plume rather than at the discharge canal exclusively as is shown in Fig. 2. Averaging water temperatures collected at several locations in the plume under various hydrothermal conditions reflects a more realistic value of the ΔT influencing the trawl transect area.

DISCUSSION

The preference of fish for the thermally affected area of the James River may be related to both physiological and ecological processes. Neill and Magnuson [11] reported that fish exposed to a power plant discharge plume during summer months either avoided or congregated in the area, and that fish distributed themselves in the plume primarily in accordance with species-specific thermoregulatory preferences. Different species tended to maximize their exposure to temperatures within a species-specific temperature range. The species that predominated the fish catches in the Surry discharge area are the spot (*Leiostomus xanthurus*), channel catfish (*Ictalurus punctatus*) and the croaker (*Micropogon undulatus*). Stauffer et al. (1975) [12] reported from laboratory experiments that 93°F (33.7°C) was the calculated preference temperature for channel catfish. However, in field studies by the same authors conducted at the Glen Lyn (Virginia) Power Plant, 90% of all channel catfish were captured at water temperatures above 94°F (34.4°C). These temperatures appear to be within the range that would be expected to occur in the plume under certain operating conditions. The FES prediction that fish would avoid the plume in summer was made assuming that temperatures in the discharge might exceed the thermal tolerance limits of certain fish species. This may in fact be occurring in the areas directly adjacent to the discharge canal; however, the trawl transects used to substantiate the prediction are likely to extend over a wide range of water temperatures since the trawls were towed from shallow inshore areas toward deep water areas offshore. There is no way to identify over which segment of the transect the majority of fish were captured. In addition, monthly fish trawls were conducted under various tidal, river flow, and plant operating conditions in which the vertical extent of the plume may have been very different from the three-dimensional projection observed in Fig. 3.

The optimal environment for growth for each species varies, but is related to the preferred temperature and the availability of food. If food organisms are abundant in the discharge area and the water temperature is within the preferred temperature range, fish will probably remain in the area. However, if food is scarce, fish may move out of the plume to search for food. In Neill's and Magnuson's study [11], fish that were living in the thermal plume area at their preferred temperature also encountered abundant food supplies. This also seems to be the case at Surry during certain periods of the year, since the discharge area generally had higher densities of benthos than the control areas [2] (Fig. 6). The three predominant species found in the Surry plume trawls (spot, croaker, and channel catfish) could take advantage of the increased benthic densities observed in the discharge, or they may be consuming dead organisms that settle to the bottom after being killed during entrainment. During operational years, fish catches in the discharge were observed to increase, while densities in various areas unaffected by the plume influences concurrently decreased. Because elevated temperatures in the Surry plume areas not only occur at the surface, but may also reach the bottom under certain hydrothermal conditions, the combination of the preferred temperatures and abundant food supply may explain the preference of fish for the discharge.

In summary, analysis of the fish monitoring data from 1971-1975 at Surry indicates that fish catches in the discharge increased, and this increase corresponded to an annual increase in the ΔT in the discharge area as Units 1 and 2 attained near maximum operating levels. This increase may be a direct result of the establishment of preferred temperature regimes in the discharge area or may be a result of the coinciding increases in the density of benthos or the addition of organisms killed by entrainment through the power plant. Although annual fish catches in the discharge area increased during the operational years, this does not indicate that increase in the standing crop or growth rates of fish in the James River also resulted; however it does indicate that some shifts in fish distribution in the vicinity of the Surry facility may have occurred. Off the Chalk Point Steam Electric Station on the middle Patuxent estuary (Virginia), no marked effects were observed on fish populations, although temporal shifts in fish distribution were reported (McErlean, 1973) [13]. At the same facility, a decline in catch rates in April was reported for the discharge, but this was thought to reflect spawning movements of the major species inhabiting the discharge area (Moore and Frisbie 1972) [14]. Predictions of the effect of the thermal discharges of Surry on the fish population of the James River (centered at Hog Point) were partially substantiated by ETS monitoring data. Fish did congregate in the plume during winter months; however, high CPEs were also observed during the summer in periods of highest water temperature. These latter results appear to contradict the prediction that fish would flee the plume in summer; however, these results may have been influenced by the location of the transects, which traverse areas at the plume periphery, and may have been influenced by methods of sampling used to evaluate the validity of the impact prediction. Detailed examination of the seasonal thermal preference temperature ranges of predominant fish species in the vicinity of Surry is needed before a definitive explanation of the observed changes in fish distribution can be made.

CONCLUSIONS

The prediction of environmental impact made in the Surry FES which was based on generally accepted ecological principles was not totally substantiated by monitoring data. Similar examples of FES predictions of impact to other trophic groups at other operating facilities which were not substantiated by monitoring data are presented by Adams et al. (1977) [2,3,4]. In assessing the validity of environmental impact predictions, three important requirements must be met. First, the impact prediction must be based on the best available information concerning the particular ecosystem under study, and the prediction must be defined in concise terms. Second, the applicant who is directly responsible for monitoring the ecosystem must design and direct the monitoring program to address the impact prediction. Third, the applicant must implement an effective monitoring program which will yield adequate data to form the basis of the information used in evaluating the prediction. In many cases one or more of these requirements are not adequately met. In some cases, an FES prediction may have been made based on less than adequate baseline data. Ideally, adequate preoperational data should be collected to establish the background conditions present prior to the introduction of the potential power plant perturbations. Generally, several years of monitoring data in this period are preferable to only one year because natural variations between years may be large, and the ecological analyst needs to understand the typical seasonal events occurring in the ecosystem under study. This background information is essential in formulating the prediction of environmental impact. The authors of the FES must also concisely define the predicted impact. For example, at Surry the exact location of the discharge or plume area needs to be known. Specific isotherms can be identified from operational data, but the question of whether the plume is defined by the extent of the 1°F, 3°F, or 5°F excess temperature contour must be answered. The utility is responsible for designing the monitoring program, and in the past, sampling programs have not always addressed predictions of impact cited in the Final Environmental Statement. In addition, some monitoring programs, while properly designed to evaluate changes, are inadequately executed; therefore, sampling is not consistently conducted, or sampling gear changes are made so that data collected over several years cannot be compared.

Clearly, the entire process of validating environmental impact predictions could be improved if a greater degree of interaction occurred between the staff responsible for analysis of environmental impacts and the utility staff responsible for designing various monitoring programs. Over the past few years, with the construction and operation of additional nuclear power plants, additional experience in environmental monitoring techniques and a better understanding of impact assessment have developed. Evaluation of the effect of power plant operations on various biota at future facilities should become more predictable if better integration is achieved between the process of formulating the impact prediction and collecting the monitoring data needed to validate the prediction.

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TABLE I. THE TOTAL AND MEAN ANNUAL FISH CATCH PER UNIT EFFORT (CPE) COLLECTED AT EACH TRAWL TRANSECT IN THE JAMES RIVER DURING THE PREOPERATIONAL PERIOD (1971-1973) AND OPERATIONAL PERIODS (1974-1975)

Station	Preoperational years (1971–1973)				Coefficient of variation	Operational years (1974–1975)				Coefficient of variation	Operational/ preoperational
	Total CPE	Total number of trawls	Mean CPE	Standard deviation		Total CPE	Total number of trawls	Mean CPE	Standard deviation		
Control											
HPSN	1573	33	47.7	51.8	108.7	872	24	36.3	40.8	112.2	0.8
Intake	1505	32	47.0	37.6	80.1	1152	24	48.0	65.0	135.4	1.0
JI	1555	33	47.1	59.3	125.9	792	24	33.0	30.7	92.9	0.7
Discharge											
DA	576	22	26.2	30.6	116.8	1065	24	44.4	44.7	100.7	1.7
DB	1021	34	30.0	31.1	103.5	1824	24	76.0	80.0	106.1	2.5
DC	608	22	29.5	38.0	129.1	2117	24	88.2	94.0	106.5	3.0

Source: 1. Virginia Electric and Power Company, *Surry Power Station Units 1 and 2, Semiannual Operating Reports, SOR1* (May 1. 1972. through December 31, 1972), *SOR2* (January 1, 1973 through June 30, 1973), *SOR3* (July 1, 1973 through December 31, 1973), *SOR4* (January 1, 1974 through June 30, 1974). *SOR5* (July 1, 1974 through December 31, 1974), *SOR6* (January 1, 1975 through June 30, 1975), *SOR7* (July 1, 1975 through December 31, 1975).

2. Surry fish trawl data (1971-1975), computer printout obtained from Virginia Electric and Power Company, February 1976.

TABLE II. THE TOTAL AND MEAN ANNUAL FISH CATCH PER UNIT EFFORT (CPE) COLLECTED AT TRAWL TRANSECTS IN CONTROL AREAS (INT, HPS-N, AND JI) AND IN THE DISCHARGE AREA (DA, DB, AND DC) IN THE JAMES RIVER

Year	Total CPE	Number of trawls	Mean CPE	Standard deviation	Coefficient of variation
			Control stations		
1971	1581	29	54.5	42.1	77.3
1972	1494	33	45.3	48.8	107.7
1973	1558	36	43.3	57.2	132.2
1974	1359	36	37.8	38.1	100.8
1975	1457	36	40.5	55.8	138.0
			Discharge stations		
1971	430	11	39.1	38.8	99.3
1972	889	31	28.7	33.1	115.3
1973	926	36	25.7	30.6	118.8
1974	1597	36	44.4	48.9	110.2
1975	3409	36	94.7	91.6	96.7

Source: 1. Virginia Electric and Power Company, *Surry Power Station Units 1 and 2, Semiannual Operating Reports, SOR1* (May 1, 1972, through December 31, 1972), *SOR2* (January 1, 1973 through June 30, 1973), *SOR3* (July 1, 1973 through December 31, 1973), *SOR4* (January 1, 1974 through June 30, 1974), *SOR5* (July 1, 1974 through December 31, 1974), *SOR6* (January 1, 1975 through June 30, 1975), *SOR7* (July 1, 1975 through December 31, 1975).

2. Surry fish trawl data (1971-1975), computer printout obtained from Virginia Electric and Power Company, February 1976.

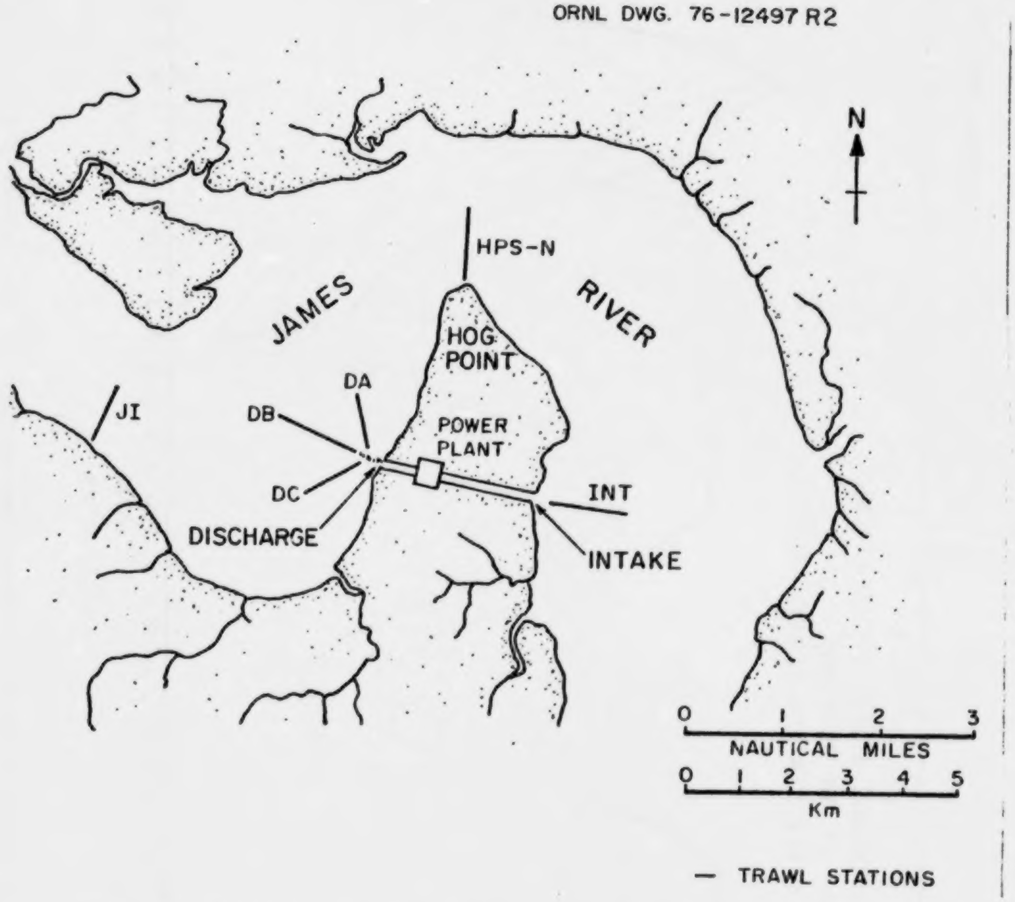
ORNL DWG. 76-12497 R2
N
HPS-N
JAMES
RIVER
HOG POINT
POWER PLANT
JI
DA
DB
DC
DISCHARGE
INT
INTAKE
0 1 2 3
NAUTICAL MILES
0 1 2 3 4 5
Km
— TRAWL STATIONS

Fig. 1. Location of the Surry Power Plant on the James River, Virginia, and Transects (DA, DB, and DC) for Fish Trawling in the Discharge Plume Area and Control Area (HPS-N, INT, and JI).

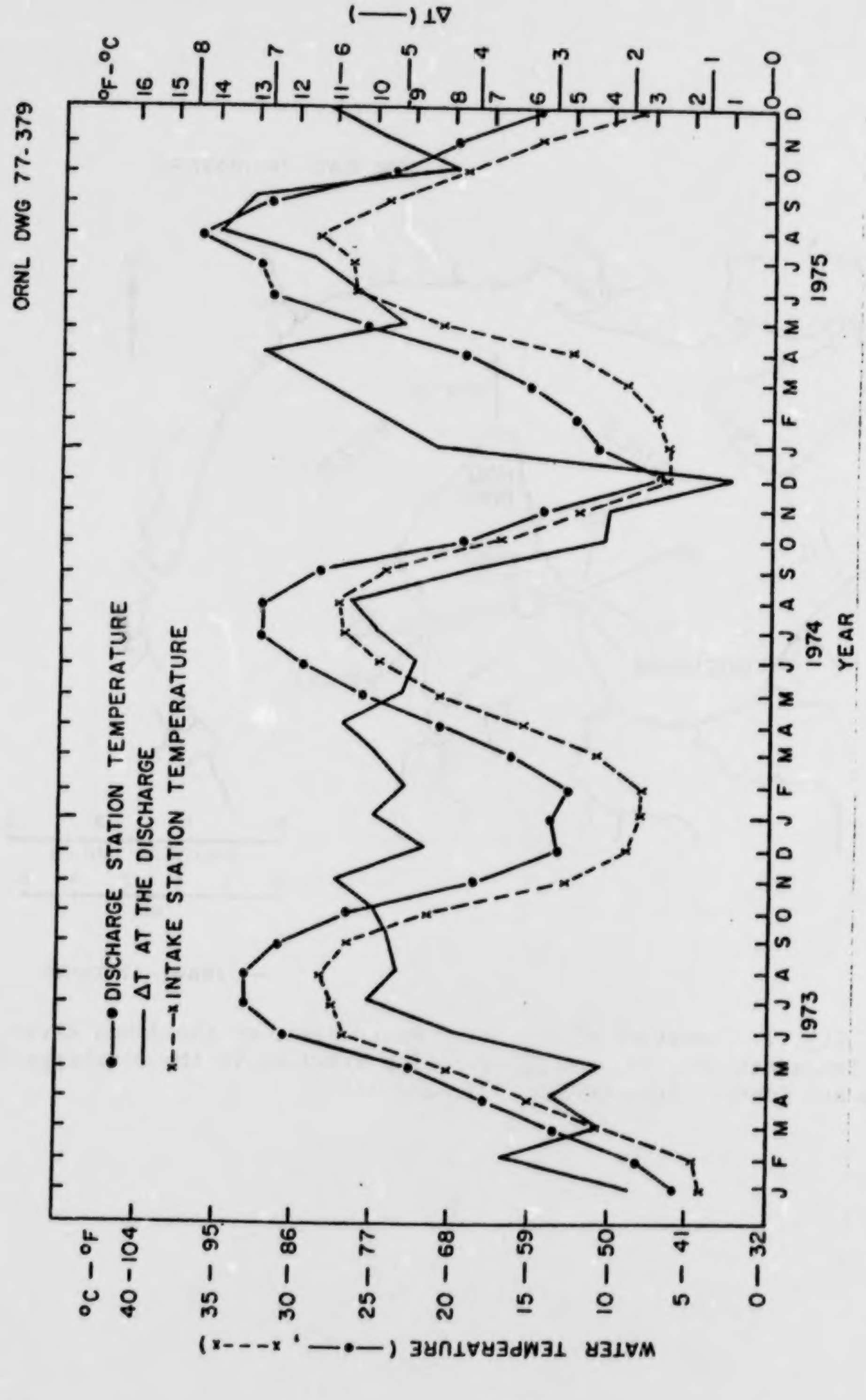

Fig. 2. Comparison of the Mean Monthly Water Temperature at the Intake (Station INT) and Discharge (Station DIS) at Surry with the Resulting ΔT as Measured at the Discharge [7,8].

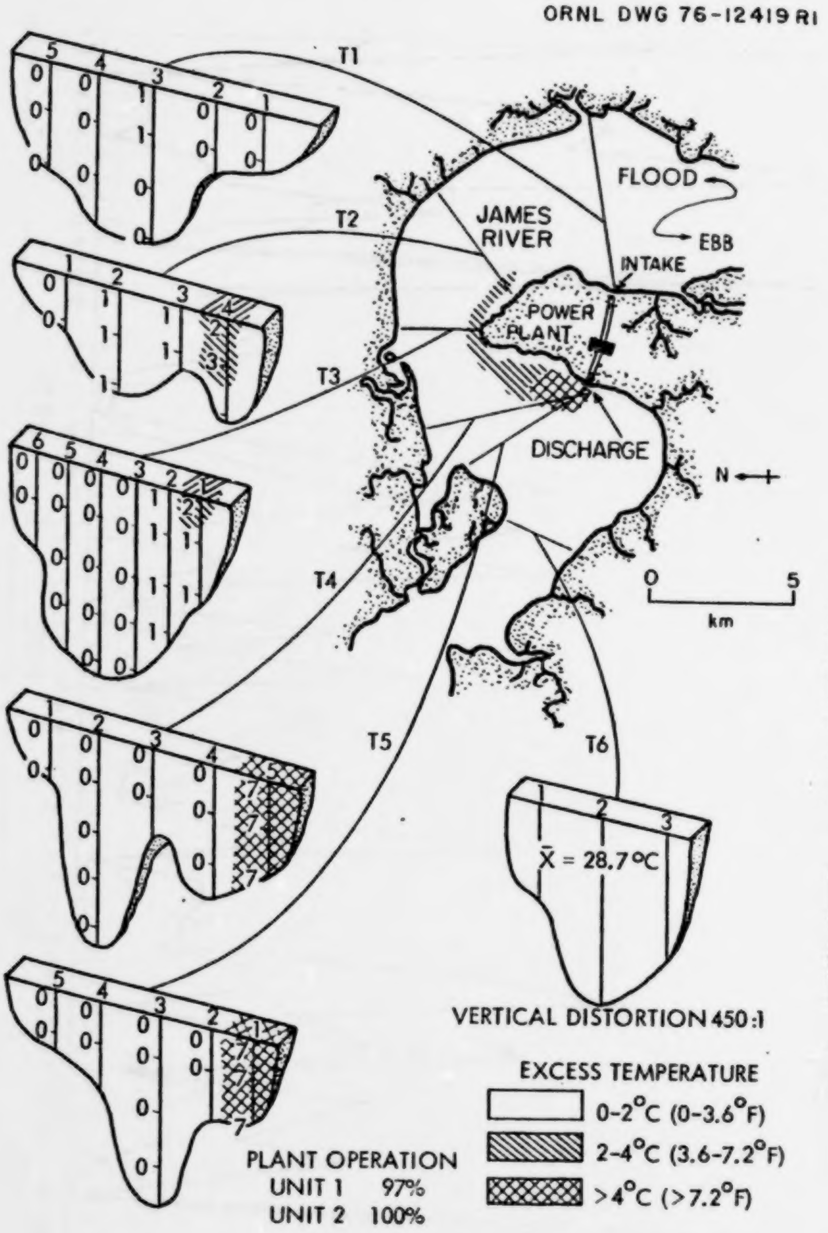
ORNL DWG 76-12419 R1
T1
T2
T3
T4
T5
T6
JAMES RIVER
FLOOD
EBB
INTAKE
POWER PLANT
DISCHARGE
N
0
5
km
X̄ = 28.7°C
VERTICAL DISTORTION 450:1
EXCESS TEMPERATURE
0-2°C (0-3.6°F)
2-4°C (3.6-7.2°F)
>4°C (>7.2°F)
PLANT OPERATION
UNIT 1 97%
UNIT 2 100%

Fig. 3. Results of a Virginia Electric Power Company Plume Survey at Surry Measured August 22, 1975, at Low Slack Water Showing the Vertical and Horizontal Extent of Three Excess Temperature Ranges with Units 1 and 2 Operating Near Maximum Capacity. Data source: Letter from C. M. Stallings, Virginia Electric Power Company, to D. R. Muller, Nuclear Regulatory Commission, August 1975.

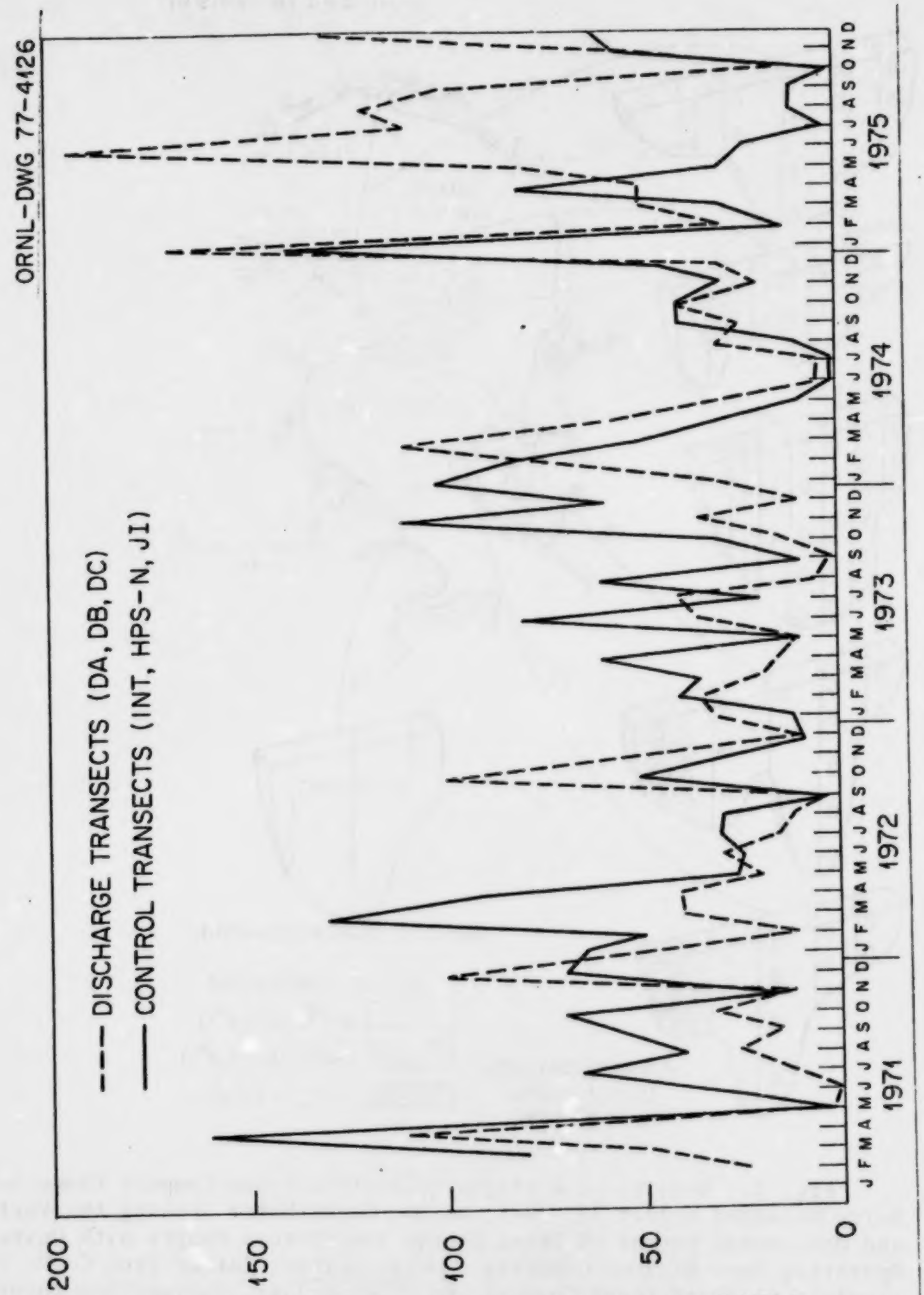

Fig. 4. Comparison of the Mean Monthly Fish Catch per Unit Effort (CPE) for the Discharge (DA, DB, and DC) and Control Areas (INT, HPS-N, and JI) at Surry (1975) [7,8].

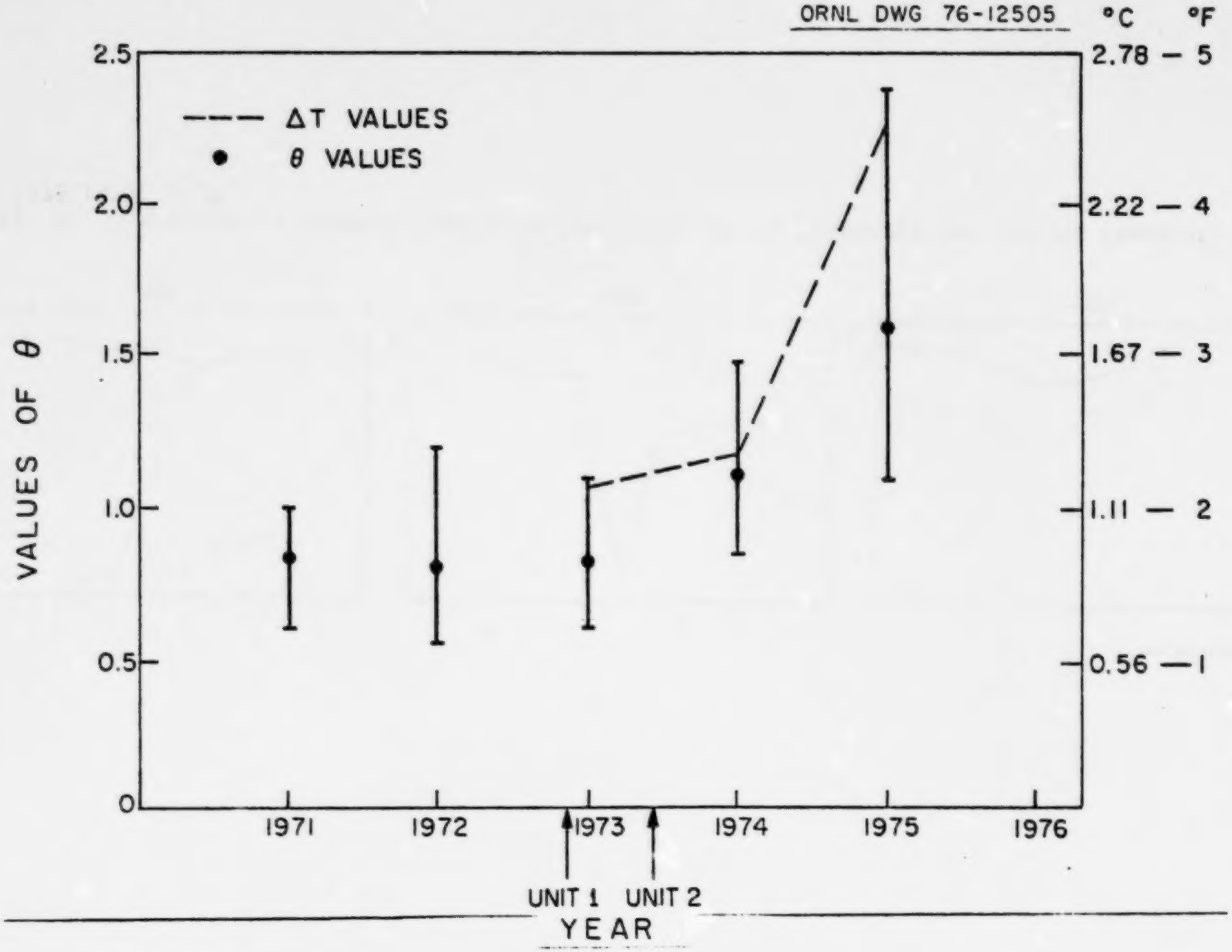

Fig. 5. Yearly Variation in the Ratio of Catch per Unit Effort (CPE) at the Discharge and Control Areas at Surry. The ΔT Values Were Computed Based on Temperature Data Collected at Several Areas Within the Discharge Plume [7,8].

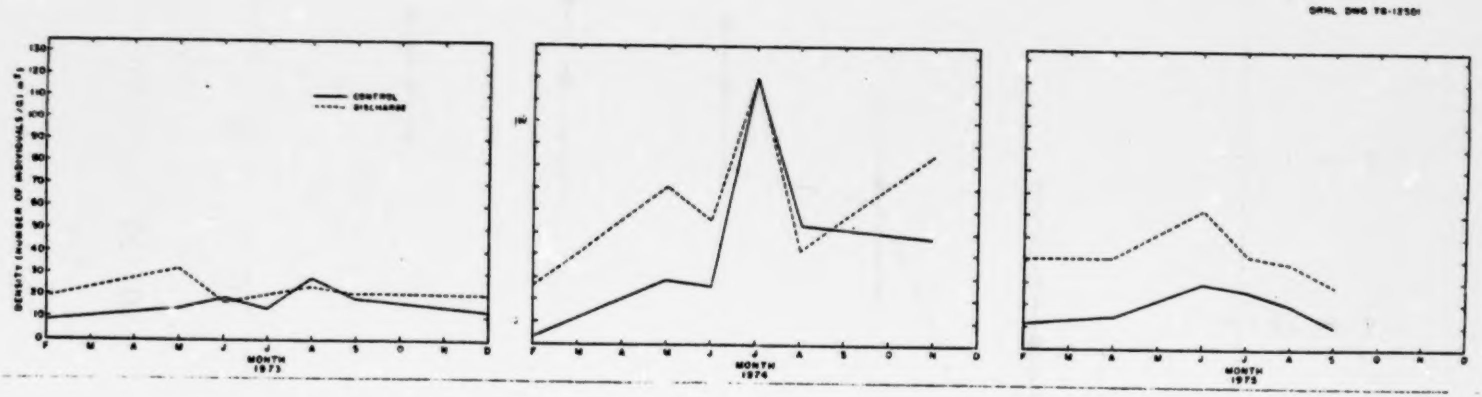

Fig. 6. Comparison of Benthic Population Densities in the Discharge and Control Areas at Surry (1973-1975) [7,8].

23-45-19

THE QUALITY AND COST OF INFERENCES CONCERNING THE EFFECTS OF NUCLEAR POWER PLANTS ON THE ENVIRONMENT

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ABSTRACT

The analysis of variance is the most common statistical procedure applied to nuclear power plant monitoring data at the present time. Under the assumption that it is appropriate, minimum detectable difference is defined and its relationship with power computed. The relationship between station number, replicate number, variance, minimum detectable difference with power of 0.90 and $\alpha = 0.10$ for phytoplankton, zooplankton, smelt and alewives at the Zion Nuclear Power Plant are given.

INTRODUCTION

Over the past ten years large quantities of data have been collected by various groups for the purpose of detecting changes in biotic communities induced by nuclear power plants. The utilities have spent millions of dollars for these data and have made inferences from it in the process of obtaining construction and operating licenses and 316a and 316b variances.

Two considerations are of paramount importance in this process: the level of change in the environment which is considered unacceptable and the ability to detect that change with the data collected. The second of these considerations depends upon the first. Both are the business of the regulatory agencies.

Without regulation regarding the intensity of studies, the logical approach for a utility is to spend as little money as possible on data collection to ensure insufficient data to detect differences, then to conclude there are no differences. On the other hand, the strategy of opponents of nuclear plants should be to insist that great effort is expended in sampling, ensuring that small differences are found statistically significant, to disregard whether the differences are real or biologically important and then to claim unacceptable damage to the environment. Both strategies are obviously unacceptable. However, until unacceptable change is clearly set forth, no scientifically acceptable procedure is obvious.

The present work deals with minimum detectable differences and the probability of detection in several experimental designs. The relationship of cost and detectable change is discussed.

MINIMUM DETECTABLE DIFFERENCES

The data collection and analysis scheme for an environmental monitoring program at a nuclear power plant is represented in Fig. 1. The concepts to be considered are shown as inputs to the various phases of the monitoring study. The data are most often collected at fixed points in time, consequently the application of intervention analysis in time series models [1] may seem appropriate. However, given the small amount of pre-operational data and such large seasonal effects, the utility of intervention analysis is not clear. The present "state of the art" relies on statistical tests such as the analysis of variance. The present work deals with the use of the analysis of variance in determining change.

At the beginning of a monitoring study an attempt is made to select stations which will be in control and effected areas once the plant is in operation. Stations are sampled periodically and the resulting data are analyzed to see if there are differences in density or catch per effort between stations. Such analyses prior to operation of the plant are useful for examining the adequacy of the stations. The same analyses applied to operational data often give some measure of plant effect but the sensitivity of the analyses depends upon the unperturbed similarity of the stations. It is worthwhile examining the ability of these tests to detect change.

The analysis performed on the data from any one sampling time uses a completely random experimental design with t stations and n replicates at each station. The ability to detect differences in the station means (Power of the statistical test) is a function of the magnitude of the differences, station number (t), of replicate number (n), and of the significance level of the test. The relationship between these variables can be seen from examination of the non-centrality parameter under an alternative hypothesis.

A reasonable alternative hypothesis to the null hypothesis of no differences is: The largest difference between station means equals Δ, that is

$$\mu_{MAX} - \mu_{MIN} = \Delta \quad , \qquad (1)$$

and all other station means are equal to the average

$$\frac{\mu_{MAX} + \mu_{MIN}}{2}.$$

μ_{MAX} is the largest mean and μ_{MIN} is the smallest station mean. This alternative hypothesis will produce minimum power for a maximum difference Δ.

The non-centrality parameter, δ, for this simple analysis of variance is

$$\delta = \left[n \sum_{i=1}^{t} (\mu_i - \bar{\mu})^2\right]^{\frac{1}{2}} , \tag{2}$$

where $\bar{\mu}$ is the mean of the station means. Imposing the above alternative hypothesis,

$$\delta = \left(\frac{n}{2}\right)^{\frac{1}{2}} \left(\frac{\Delta}{\sigma}\right) , \tag{3}$$

where σ is the common within-station variance. As the number of stations, t, changes, the treatment and residual degrees of freedom change. The Pearson-Hartley [2] charts for power incorporate this change by requiring the computation of a parameter, ϕ, where $\phi = \dfrac{\delta}{\sqrt{t}}$. Hence, $\phi = \{\frac{n}{2t}\}^{\frac{1}{2}}\{\frac{\Delta}{\sigma}\}$, and as ϕ gets larger the power increases. For fixed minimum detectable difference, Δ, the probability of detection (power) increases as n increases, as t decreases, and as σ decreases.

To illustrate the relationship between n, t, Δ, and power, a variance of 0.25 will be used. This is the approximate variance if a square root transform is applied to observations modelled with the Poisson distribution.

Number of Replicates (n)

Power as a function of the minimum detectable difference Δ for different number of samples per station is illustrated for $t = 2$ (Fig. 2) and for $t = 4$ (Fig. 3). For a given power considerable reduction is made in the difference detectable (Δ) with an increase from 2 to 8 replicates. For example (Fig. 3), with power of 0.90, $\Delta = 3.15$ with 2 replicates and $\Delta = 1.0$ with 8 replicates.

The relationship between minimum detectable difference and number of replicates per station for different levels of probability of a type I error (α) is illustrated for power of 0.85 (Fig. 4) and power of 0.95 (Fig. 5). As the number of replicates increases, Δ decreases. The decrease in Δ is large in going from $n = 2$ to $n = 8$, but after $n = 8$ the change is much less. It is also observed that for a fixed number of replicates the minimum detectable difference decreases as α increases.

Number of Stations (t)

Fig. 6 shows the relationship between power, n, and t. The total number of samples (nt) is held constant at 24. For a fixed minimum detectable difference, power is seen to increase as t decreases and as n increases. This relationship is relevant to monitoring designs, whether two or twelve stations are used, if the stations with μ_{MAX} and μ_{MIN} are always included in the design.

Variance (σ^2)

Fig. 7 shows the relationship between the detectable difference and standard deviation (σ) for n = 2, 4, 8 and t = 2 and 4 with power of 0.95. The increase in the minimum detectable difference is almost a linear function of increasing standard deviation. It is also observed that the smaller the replicate number the greater the effect of increasing standard deviation.

Percent Minimal Difference

The minimal detectable difference is in absolute units of measurement, e.g., numbers of organisms per ml, number per Ponar dredge, mg per liter or catch per minute. The interpretation of a detectable difference of Δ units will vary with the magnitude of the means. If $\Delta = 2$, with power of 0.95 and $\mu_{MAX} = 20$, a reduction of 10% could be detected with probability 0.95. If, however, $\mu_{MAX} = 200$ and all other parameters were still the same, then a 1.0% change could be detected with 0.95 probability. Consequently, minimum detectable difference should always be related to the magnitude of the station means. This is a problem in monitoring designs, since the means fluctuate seasonally. A certain sample size might ensure the detection of a 10% change in summer but only a 50% change in winter. Regulatory agencies will have to address this problem.

Preoperational-Operational Comparisons

The comparison of preoperational and operational data can be accomplished in several ways. Preoperational and operational data from stations in influenced areas can be compared, but since the data are collected in different years environmental effects are often confounded with plant effects. If environmental differences between years affect both control and influenced stations in a similar manner, plant effect can be determined by comparing preoperational-operational differences at control and influenced stations. A factorial treatment design can be used for this comparison by testing the interaction hypothesis in the following 2 x 2 design.

	Control	Influenced
Preoperational	μ_{11}	μ_{12}
Operational	μ_{21}	μ_{22}

Interaction Hypothesis: $\mu_{11} - \mu_{21} = \mu_{12} - \mu_{22}$.

To determine the probability of detecting an effect Δ, i.e.,

$$\mu_{11} - \mu_{21} - (\mu_{12} - \mu_{22}) = \Delta \qquad (4)$$

the non-centrality parameter becomes,

$$\delta = \left(\frac{n}{4}\right)^{\frac{1}{2}} \left(\frac{\Delta}{\sigma}\right) = \left(\frac{n}{2}\right)^{\frac{1}{2}} \left(\frac{\Delta}{\sqrt{2\sigma}}\right) \qquad (5)$$

Consequently, the previous power curves can be used with variance $2\sigma^2$ instead of σ^2, $t = 2$, and number of replicates equal to $2n-1$.

APPLICATION TO IMPACT STUDIES

The major problem in using the analysis of variance with monitoring data is that the normal distribution is not often a good model. There are exceptions, however, since the central limit theorem applies if means are used as observations, and many discrete distributions converge to the normal when the values of parameters get large. Often the sampling can be arranged to increase parameter values so that the normal distribution can be used. This can be accomplished with the Poisson or negative binomial by increasing the sample size, i.e., more water, more substrate, or more trawling time.

When the normal distribution can be used, we are often faced with unequal variances. With equal sample size this is less of a problem since the robustness is greater with equal sample sizes. Transformations are often applied to transform the observations into random variables with equal variance. Transformations, however, will interfere with the test of impact in some situations. For example, if a $\log_e$ transform is applied to catch-per-effort data modelled with the log-normal distribution, the test of the interaction hypothesis may be invalid, since

$$H_o : \mu_{11} - \mu_{21} = \mu_{12} - \mu_{22} \qquad (6)$$

in the $\log_e$ scale does not imply

$$H_o : e^{\mu_{11}} - e^{\mu_{21}} = e^{\mu_{12}} - e^{\mu_{22}} \qquad (7)$$

in the untransformed scale. Hence transformations may remove or create statistical significance of impact in factorial treatment designs. The problem is not encountered in the one-way designs. In most situations, particularly with equal sample sizes, it is better to rely on the robustness of the analysis of variance and not transform the data.

The other problem with using power functions to determine minimum detectable differences and sample size is the unknown variance. Figs. 8 and 9 present estimated monthly variances computed from the 1973 monitoring data from the Zion Nuclear Power Plant. The data are total zooplankton and total phytoplankton densities and catch per minute for alewives and smelt. It is observed that considerable variability exists in the estimates. No particular seasonal pattern is obvious, although a pattern might be expected for the seasonal change in density. To be able to approximate the power function, the variances can be pooled to arrive at a reasonable estimate. The power functions are conditional on the choices of σ^2

Review of the 1973 Zion Nuclear Power Plant data [3] allows a comparison of minimum detectable difference with average density of all the stations. These values are presented in Table 1. The data for phytoplankton and zooplankton were square root transformed and the catch-per-effort data was $\log_e$ transformed prior to analysis.

A computation of % detectable difference can be obtained by considering

$$\left(\frac{\Delta}{\overline{X}}\right)100 = \text{percent change detectable} \qquad (8)$$

where $\overline{X}$ is the annual average for the variable of interest.

This quantity is useful in relating the detectable difference to the average density found in the environment. These quantities are given in Table 1.

With catch per effort the log normal distribution is often used as a model. The $\log_e$ transform is applied and the analysis of variance is used to make inferences about the parameter μ. Since the median of the log normal distribution is e^{μ}, making inferences about μ in the transformed scale allows us to make inferences about the median in the untransformed scale.

$$\Delta = \mu_{MAX} - \mu_{MIN} \qquad \text{transformed scale}$$

$$e^{\Delta} = \frac{e^{\mu_{MAX}}}{e^{\mu_{MIN}}} \qquad \text{untransformed scale} \qquad (9)$$

Consequently, the measure of change is the ratio of the largest to smallest median, which is clearly a reasonable measure of change.

The usual number of replicates varies between one and four for most monitoring studies reviewed. With one replicate very little can be said, since no change can be detected. With four replicates considerable sensitivity results. Review of Figs. 3 and 4 indicates that above eight replicates small decreases in the minimum detectable difference are accomplished by further increasing the number of replicates. However, as the number of replicates increases, so does the cost of the study. Since the cost of the study is passed on to the public, this cost must be compared to the costs associated with changes in the environment due to plant operation.

COST OF DETECTING CHANGE

Minimum detectable difference and cost of monitoring are both functions of the number of stations and the number of samples collected at each station. Cost increases as the number of total samples (nt) increase since collection time and sample analysis time increase as the number of samples increase. If the station number (t) is fixed a simple first approximation to the cost function is given by the linear function,

$$f_t(n) = C_0 + C_1nt + C_2nt$$

C_0 = fixed cost of collection per sample
C_1 = cost of collection per sample
C_2 = cost of analysis per sample

This function is an oversimplification of the true cost function but will give an approximation to the relationship between cost and difference detectable. Detectable difference at fixed power is obtained from the non-centrality parameter (δ),

$$\Delta = \left[\frac{2}{n}\right]^{\frac{1}{2}} [\sigma\delta]$$

Fig. 10 shows the relationship between cost and Δ when $C_1 = C_2 = \frac{1}{2}$. The essential feature is that the cost rises very rapidly for studies capable of detecting small environmental changes.

It is recommended that the regulatory agencies should make a concerted effort in defining unacceptable environmental change and then insist upon monitoring studies capable of detecting such changes. Examination of power functions will be helpful in this regard.

LITERATURE CITED

1. Box, G.E.P. and G.C. Tiao, 1975. "Intervention Analysis with Applications to Economic and Environmental Problems," Jour. Am. Stat. Assoc. 70:70-79.
2. Pearson, E.S. and H.O. Hartley, 1954. Biometrika Tables for Statisticians, Vol. 1, Cambridge University Press.
3. Industrial Bio-Test Laboratories, 1975. "Evaluation of Thermal Effects in Southwestern Lake Michigan, Special Studies 1972-73." Report to Commonwealth Edison Company, Chicago, Illinois.

TABLE 1. ANNUAL AVERAGE, $\overline{X}$, SAMPLE VARIANCE, $\hat{\sigma}^2$, SAMPLE STANDARD DEVIATION, $\hat{\sigma}$, MINIMUM DETECTABLE DIFFERENCE IN THE TRANSFORMED SCALE, Δ, MINIMUM DETECTABLE DIFFERENCE IN THE UNTRANSFORMED SCALE, e^{Δ}, AND PERCENT CHANGE DETECTABLE, COMPUTED FROM THE 1973 MONITORING DATA FROM THE ZION NUCLEAR POWER PLANT.[a]

	Zooplankton	Phytoplankton	Alewives	Smelt
$\overline{X}$	179.5	38.23	3.33	1.30
$\hat{\sigma}^2$	133.10	16.73	2.40	2.95
$\hat{\sigma}$	11.54	4.09	1.55	1.72
$\Delta = \mu_{MAX} - \mu_{MIN}$	28.0	10.9	4.1	4.7
$e^{\Delta} = \frac{e^{\mu_{MAX}}}{e^{\mu_{MIN}}}$	-	-	60.3	110.0
% change detectable	15.6	28.5		

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[a] Power = 0.90, $\alpha = 0.10$

Zooplankton and Phytoplankton data ($\#/m^3$) are square root transformed and CPUE (catch/minute) are $\log_e$ transformed prior to analysis.

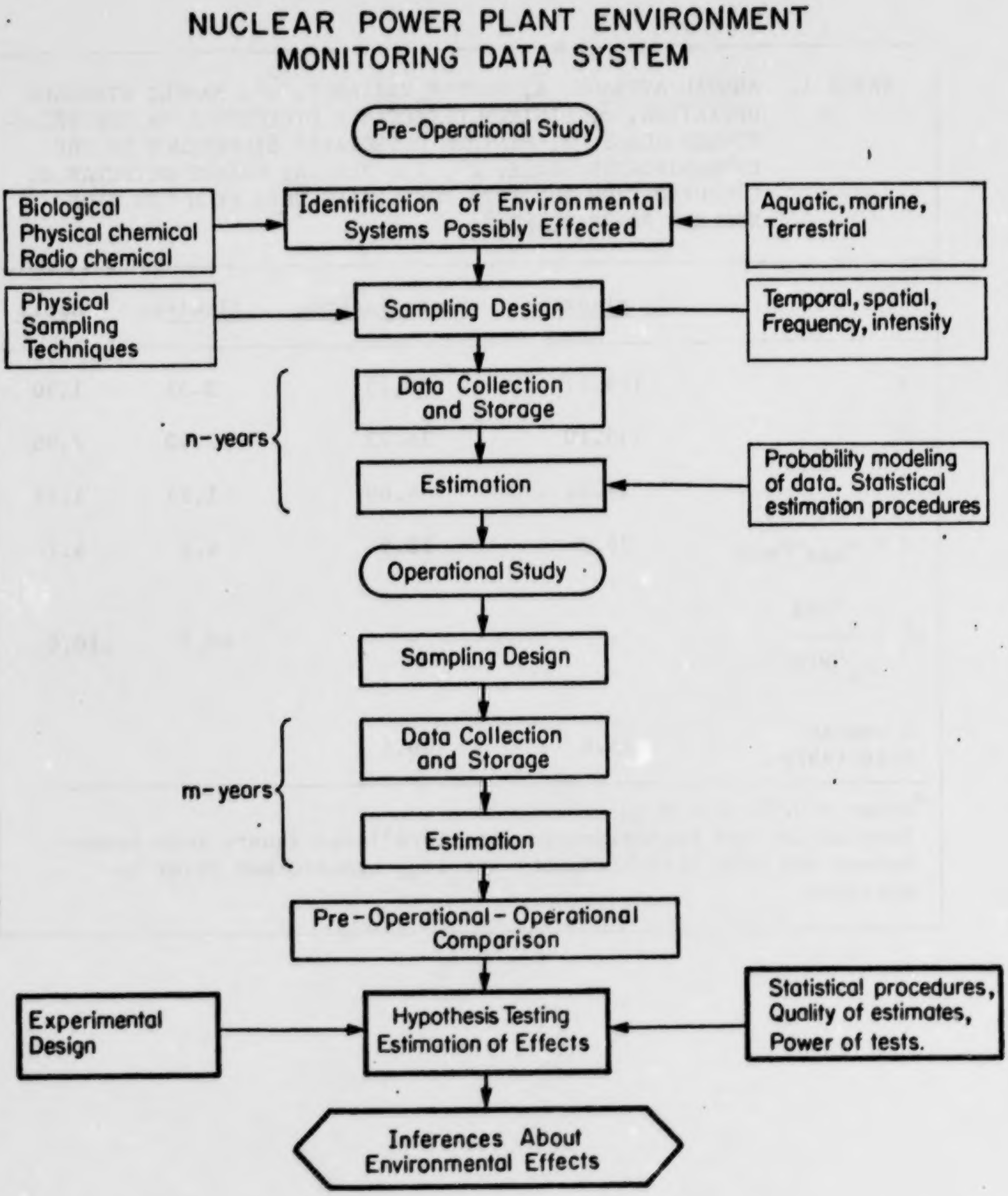
NUCLEAR POWER PLANT ENVIRONMENT
MONITORING DATA SYSTEM
Pre-Operational Study
Biological
Physical chemical
Radio chemical
Identification of Environmental Systems Possibly Effected
Aquatic, marine, Terrestrial
Physical Sampling Techniques
Sampling Design
Temporal, spatial, Frequency, intensity
n-years
Data Collection and Storage
Estimation
Probability modeling of data. Statistical estimation procedures
Operational Study
Sampling Design
m-years
Data Collection and Storage
Estimation
Pre-Operational - Operational Comparison
Experimental Design
Hypothesis Testing Estimation of Effects
Statistical procedures, Quality of estimates, Power of tests.
Inferences About Environmental Effects

Figure 1. Typical data collection and analysis scheme for an environmental monitoring program at a nuclear power plant.

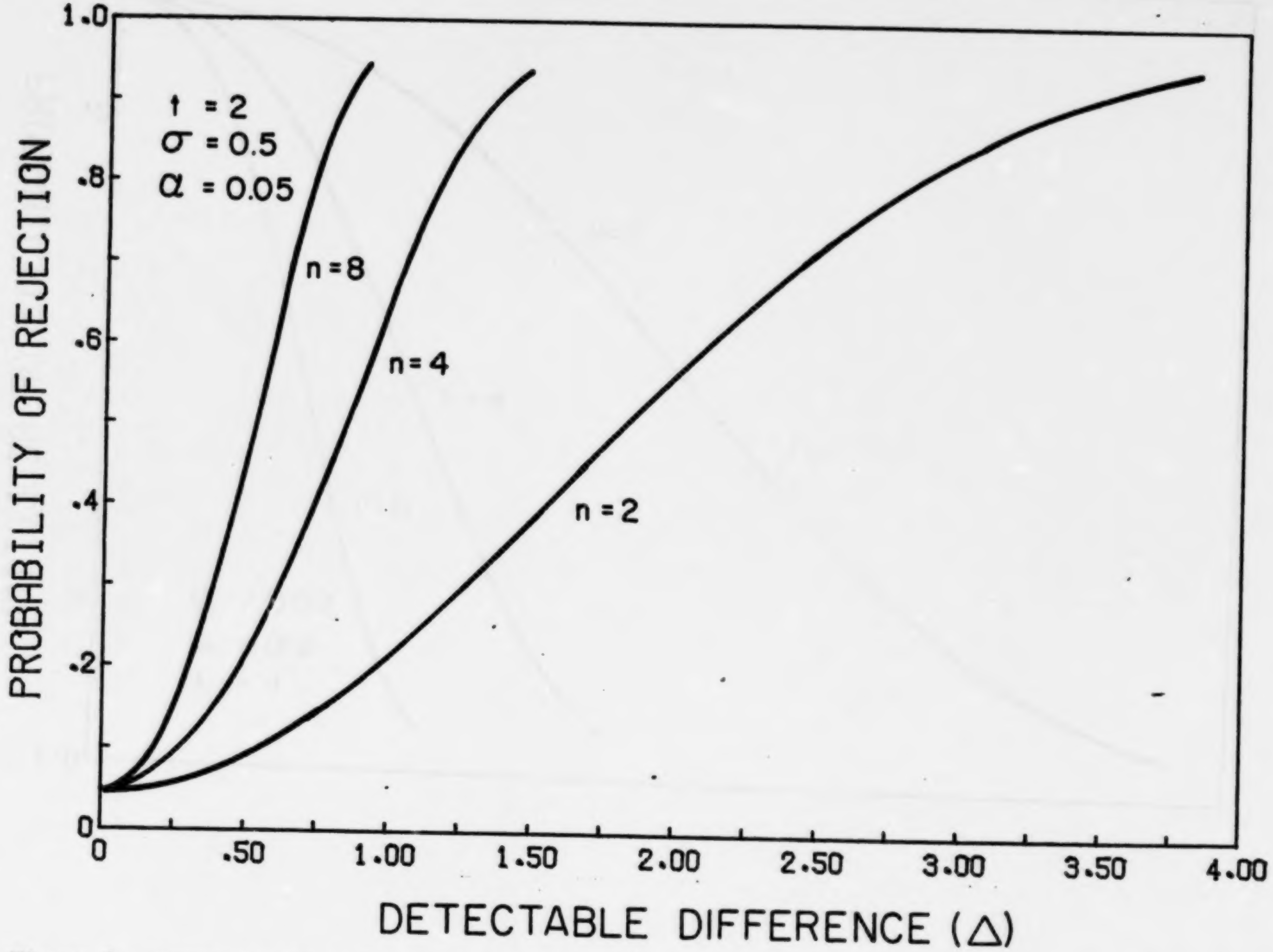

Figure 2. Power function for two stations and 2,4,8 replicate samples at each station. Significance level $\alpha = 0.05$ and standard deviation $\sigma = 0.5$.

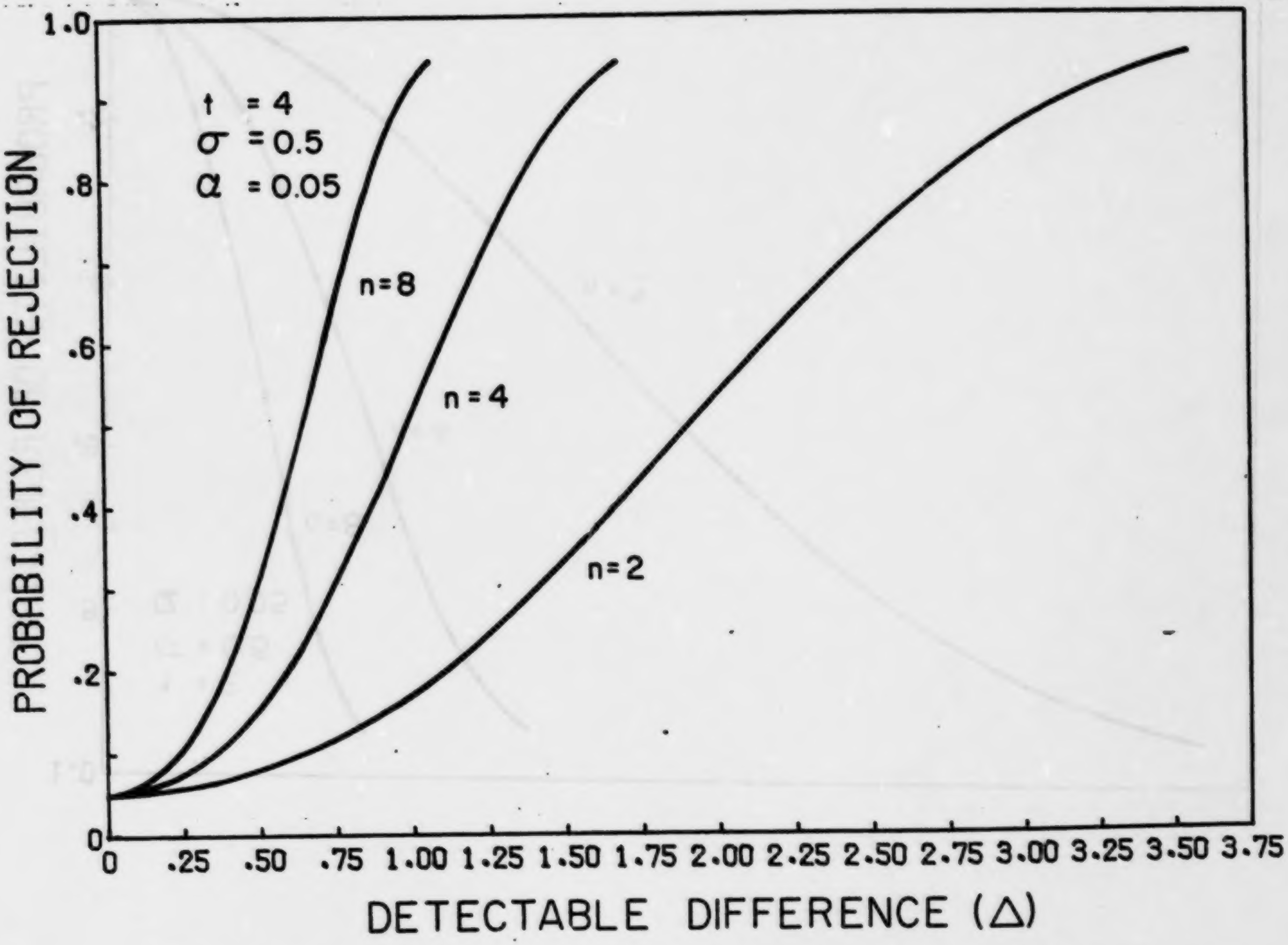

Figure 3. Power function for four stations and 2,4,8 replicate samples at each station. Significance level α = 0.05 and standard deviation α = 0.5.

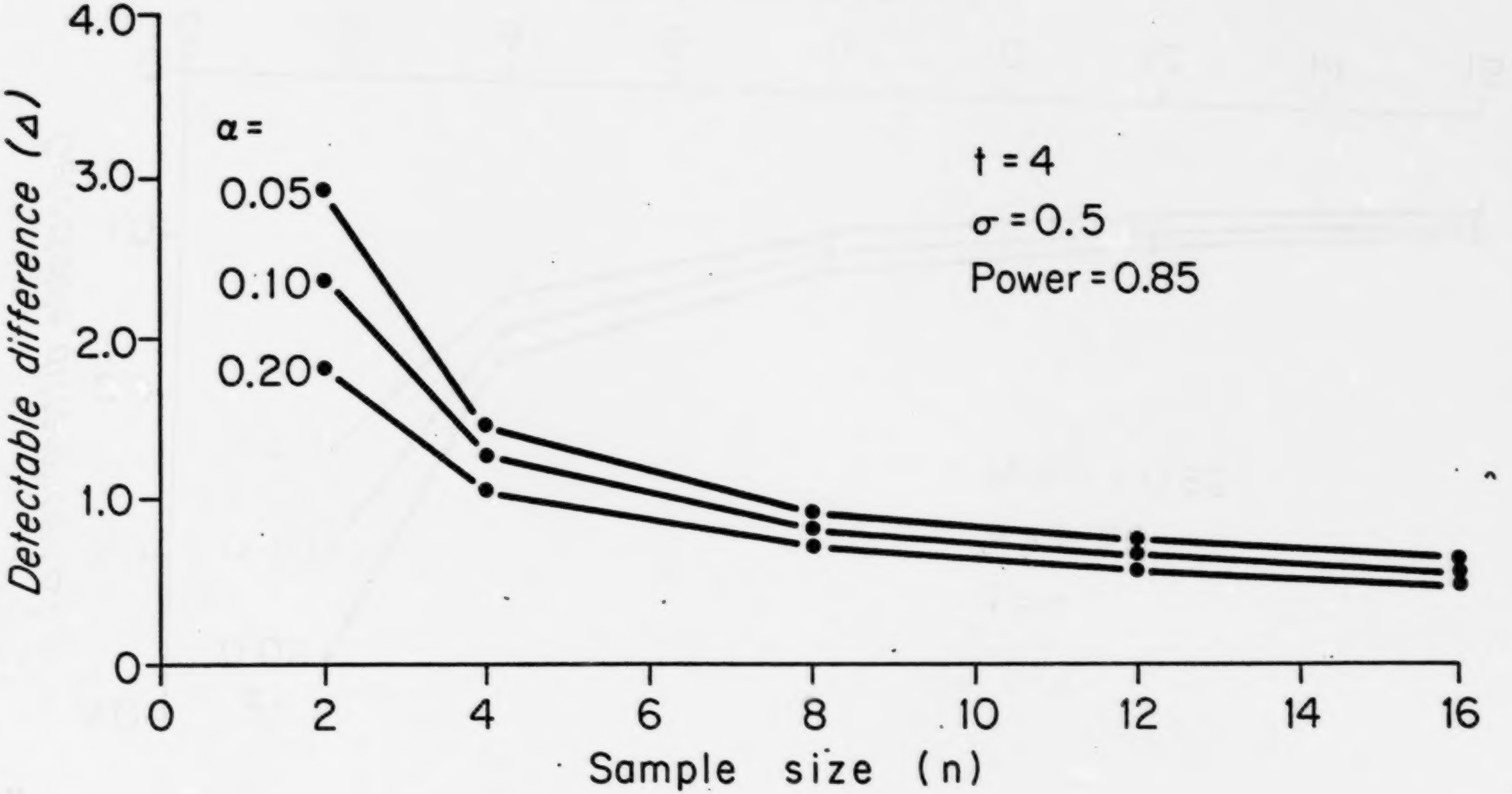

Figure 4. Minimum detectable difference as a function of replicate number (n) for four stations (t) with 0.85 probability of detection, $\alpha = 0.05$, 0.10 and 0.20 and $\sigma = 0.5$.

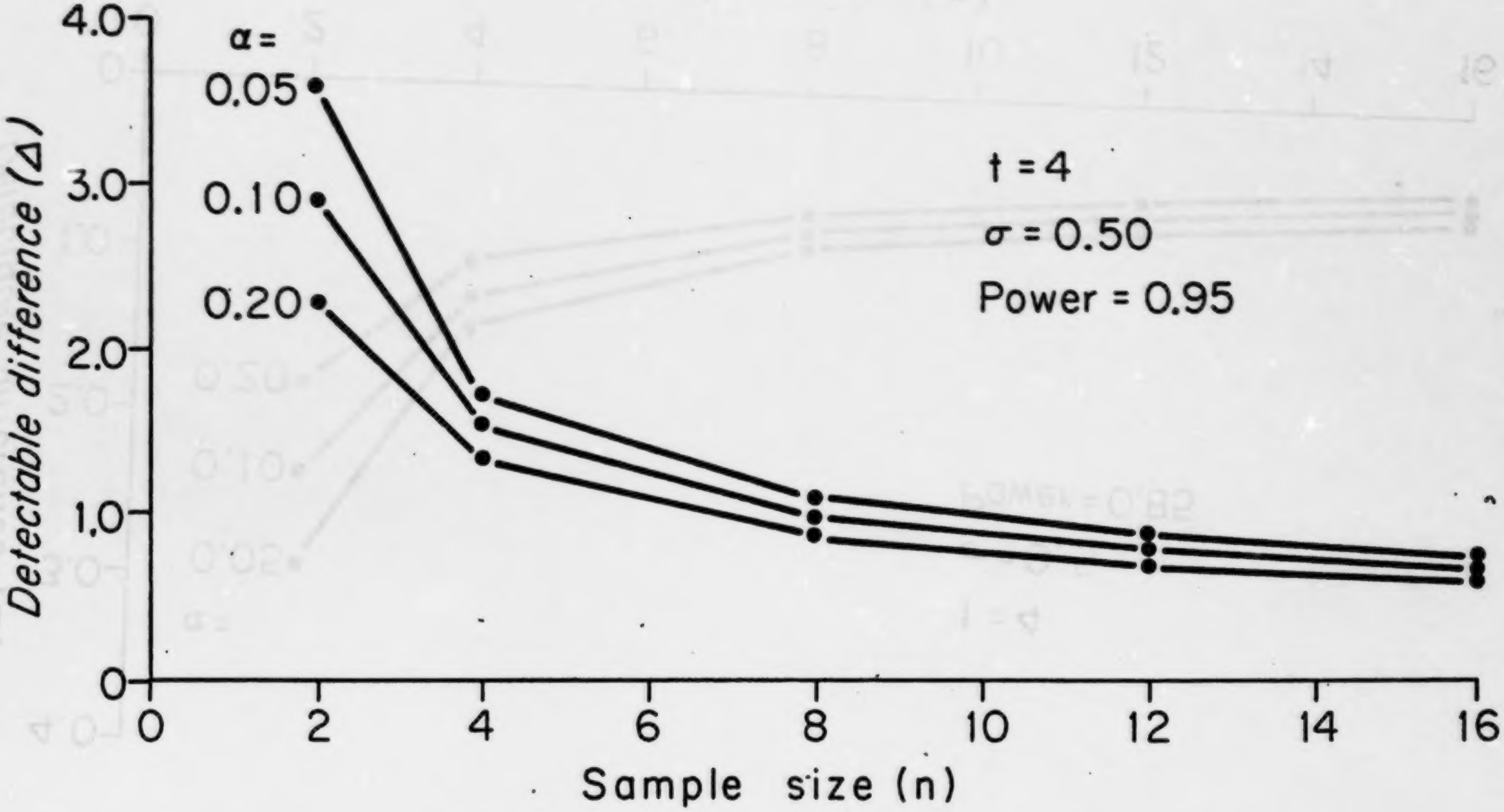

Figure 5. Minimum detectable difference as a function of replicate number (n) for four stations (t) with 0.95 probability of detection, α = 0.05, 0.10 and 0.20 and σ = 0.5.

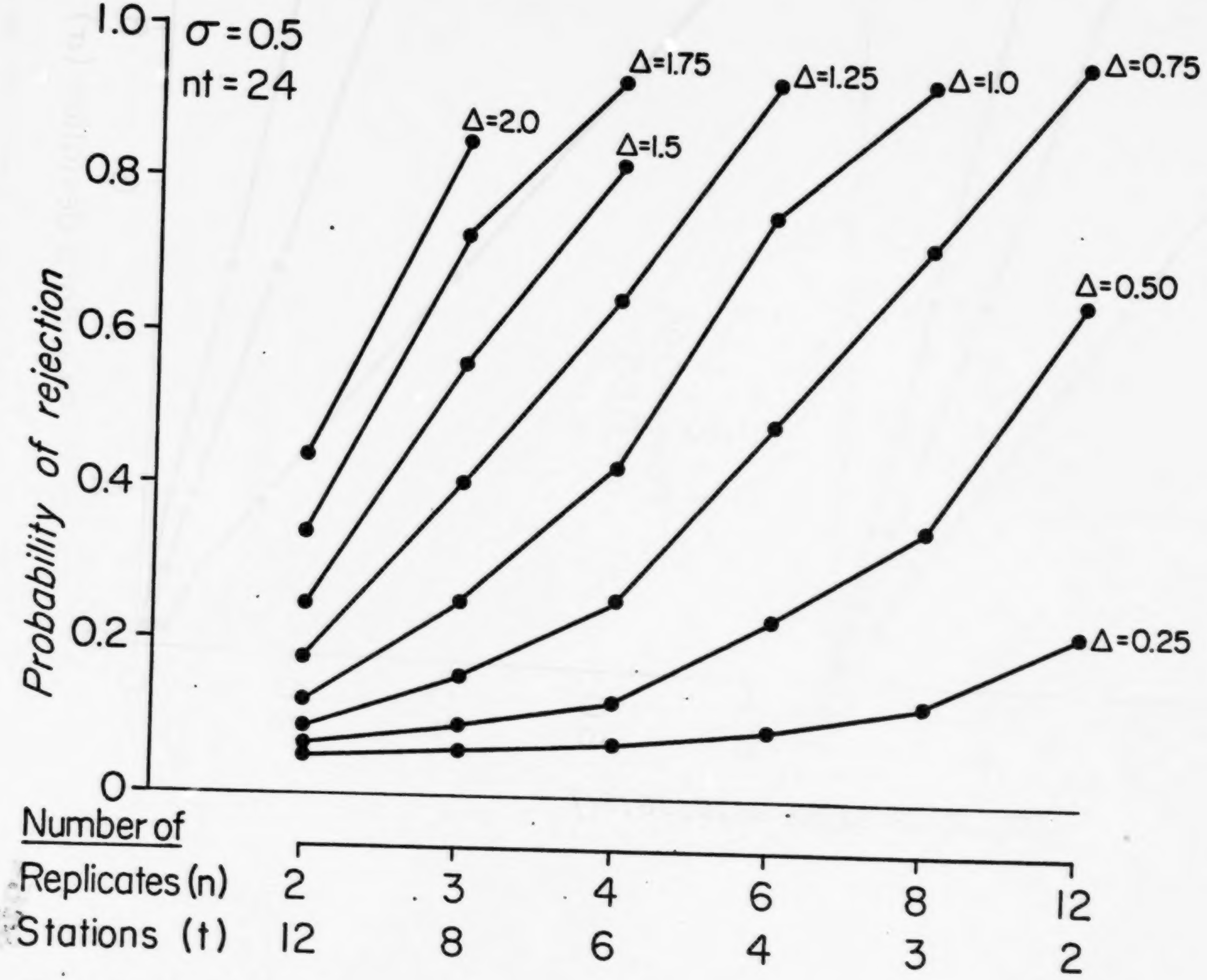

Figure 6. Probability of detection as a function of station number (t) and replicate number (n) with constant sampling effort nt = 24, σ = 0.5.

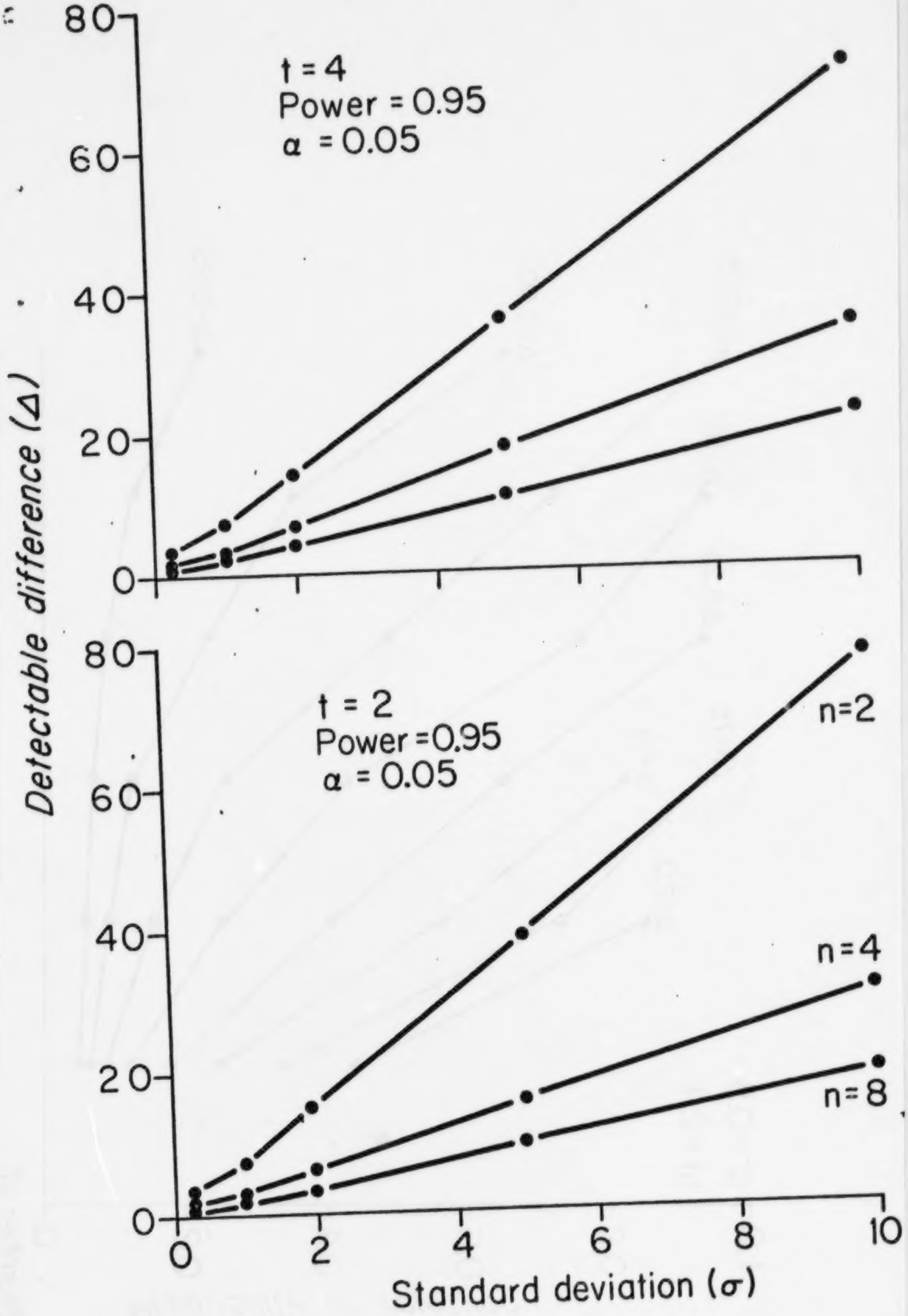

Figure 7. Minimum detectable difference as a function of the standard deviation (σ) for h = 2,4,8 and probability of detection 0.95

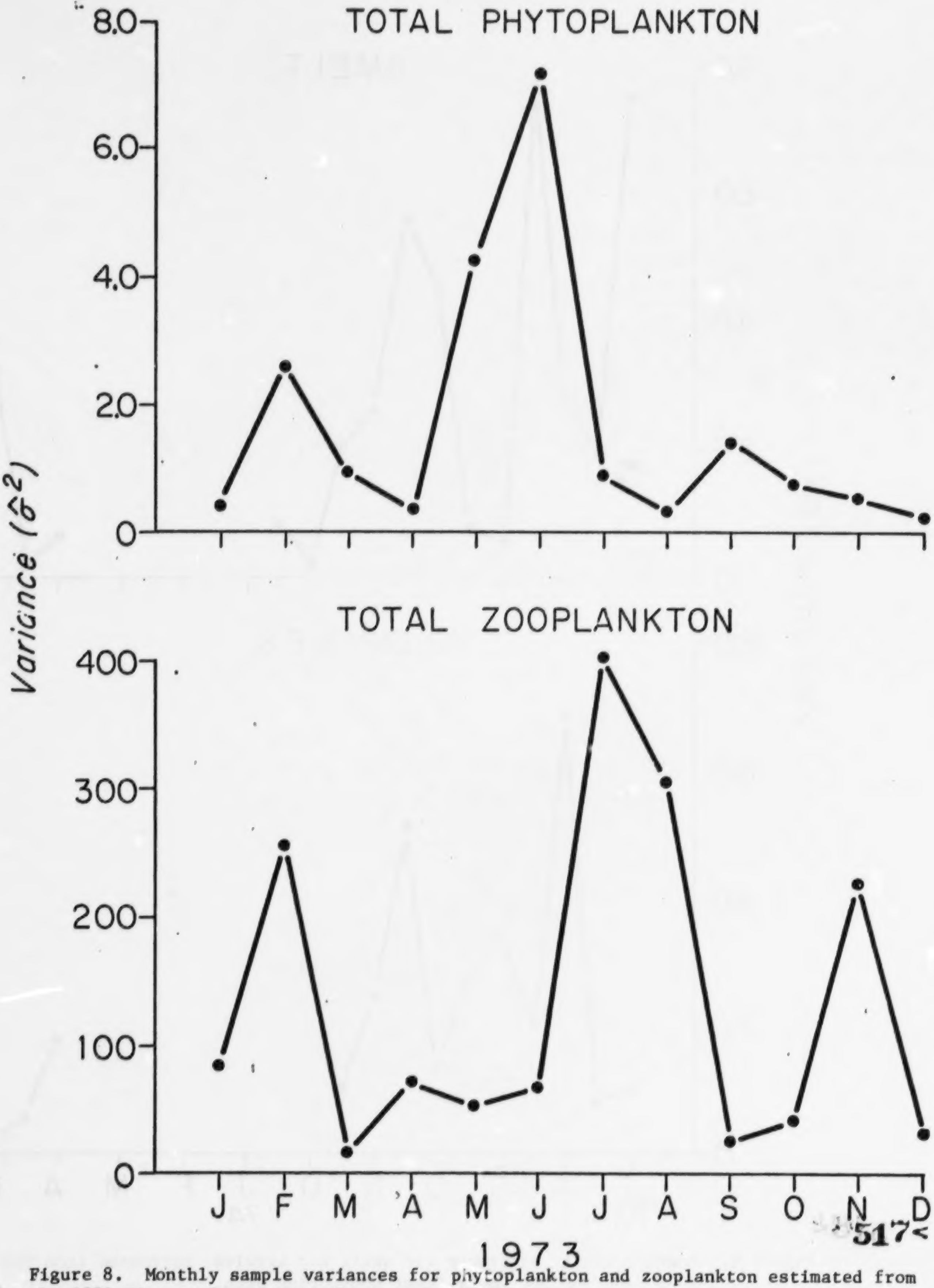

Figure 8. Monthly sample variances for phytoplankton and zooplankton estimated from the 1973 Zion nuclear power plant monitoring data.

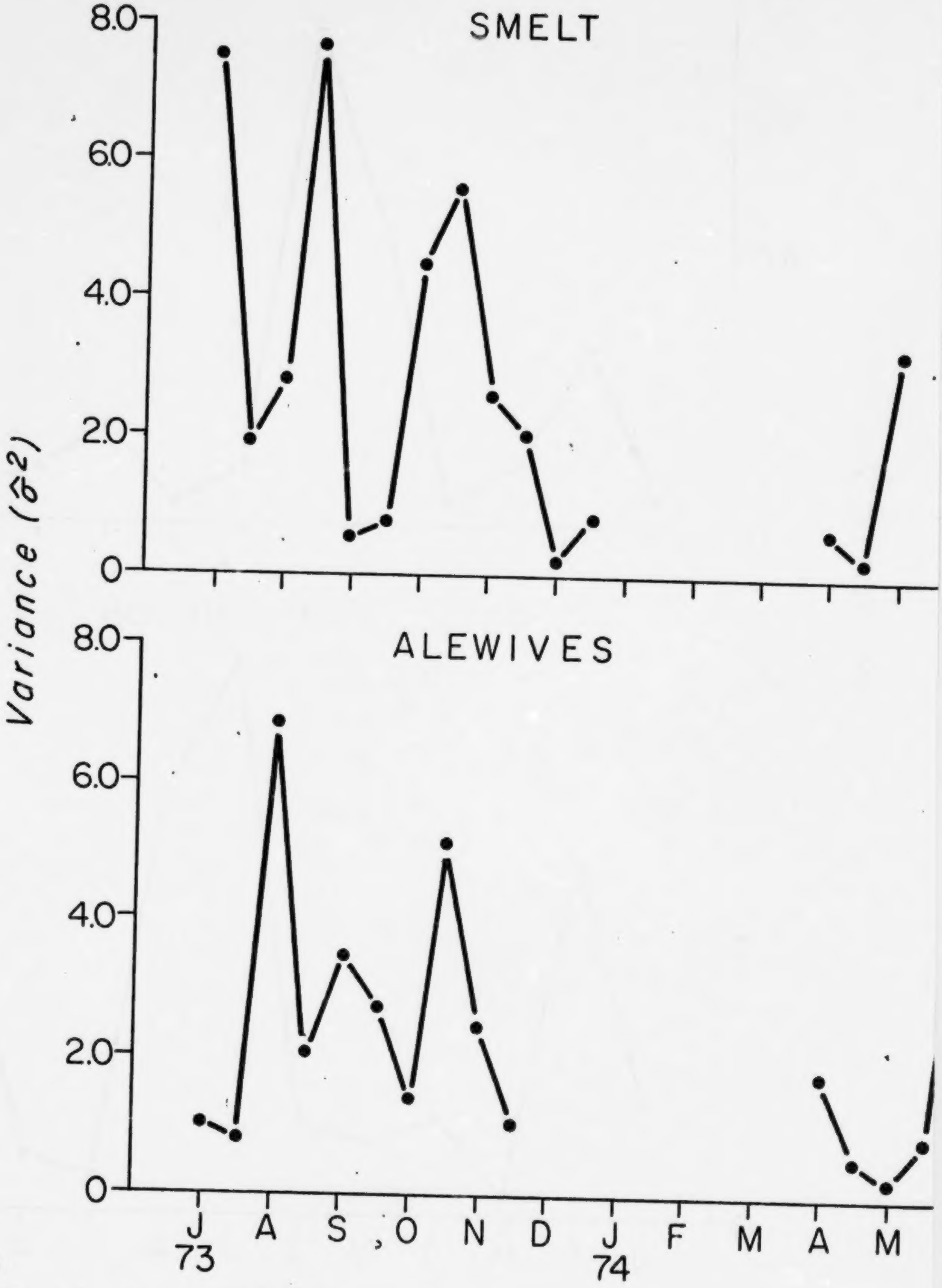

Figure 9. Monthly sample variances for smelt and alewives estimated from the 1973 Zion Nuclear Power Plant monitoring data.

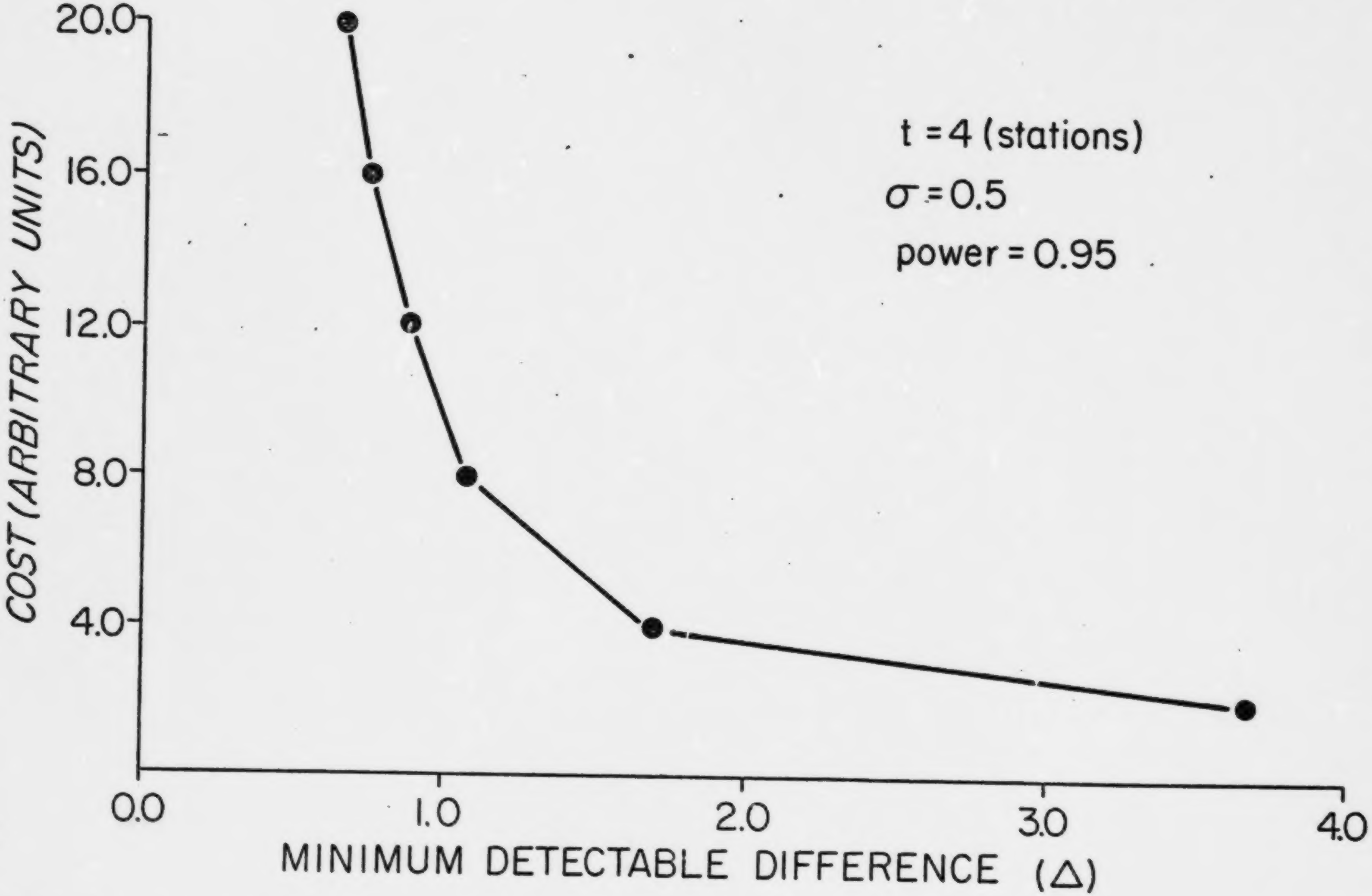

Figure 10. Cost as a function of minimum detectable difference, the cost is in arbitrary units.

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omit

THE STATE OF THE ART OF ENVIRONMENTAL AND THERMAL PERFORMANCE MONITORING TECHNIQUES FOR CLOSED-CYCLE COOLING SYSTEMS

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ABSTRACT

Newly installed power generating plants are using closed-cycle cooling systems, mainly cooling towers, at an increasing rate for waste heat rejection. This has triggered the interest of primarily regulatory agencies in the potential environmental effects of such cooling systems, and increased the utility industry's interest in accurate assessments of cooling tower thermal capabilities.

Knowledge of potential environmental effects of these systems was by and large nonexistent about five years ago. It therefore became necessary to develop test equipment and procedures in order to acquire data that could serve as a foundation for evaluations and decisions. This paper presents the state of the art of environmental monitoring on closed-cycle cooling systems in the two areas of primary interest:

1. Source Emission and Atmospheric Dispersion Measurements.

   Described are instrumentation and experimental procedures to measure the vapor plume parameters: wet- and dry-bulb air temperature, updraft air velocity, and total liquid water content; and the drift parameters: droplet mass flux, droplet size distribution, and drift mineral mass flux. Drift fallout measurements at ground level downwind of the source are also discussed.

2. Noise Measurements

   Described are instrumentation and experimental techniques for measuring sound pressure levels. Octave band sound pressure levels, weighting curves, and sound attenuation methods are discussed.

Additionally presented are new techniques for monitoring the thermal performance and acceptance of cooling systems. Major refinements of thermal performance test procedures and instrumentation began only about three years ago. Efforts were primarily directed towards the development of instrumentation capable of measuring concurrently a multitude of parameters at multiple test locations as is required for today's large cooling systems. This instrumentation and the experimental techniques for measuring circulating water flow rates, hot and cold water temperatures, inlet air wet- and dry-bulb temperatures are presented.

For all areas, representative data are presented and discussed.

SESSION XI-A
OPEN SESSION I

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ABSTRACT

Effects of Power Plant Induced Mortality on Neomysis and Striped Bass Populations

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Results of investigations related to power plant operation in the San Francisco Bay-Delta are described. Data related to plant operation for the years 1967 to 1976 are given in the form of weekly average power production and discharge temperatures.

Field studies were conducted to quantify the number of Neomysis and young striped bass which were entrained during 1976. These numbers were compared to mid-channel concentrations. It was found that the average concentration of Neomysis in the plant intake was approximately one-half the concentration found at mid-channel. Previous estimates of Neomysis mortality due to plant operation could therefore be a factor of two too high. No significant difference between striped bass concentrations at mid-channel and intake was found.

Data from the California Department of Fish and Game striped bass "Tow Net Surveys" were used in conjunction with computed percent survival data (Kelley & Chadwick, 1971) to estimate numbers of "young of the year" striped bass killed by plant operation. The computed numbers killed and specific loss rates were compared to irrigation losses, export losses, and the specific rate of population decline. It was found that two power plants combined could account for from four to eight percent (4-8%) of the observed total loss rate.

A non-linear regression analysis of factors affecting young-of-the-year (YOY) striped bass abundance indicated that Delta outflow was significantly correlated with YOY abundance. A multivariate

linear regression using predicted values from the non-linear polynomial regressions was significant at the ninety-five percent (95%) confidence level with an R^2 value of 0.915.

Factors affecting recruitment of three year old bass to the population were investigated by regression analysis. Again, Delta outflow three years earlier was significantly correlated with recruitment. A multivariate linear regression was significant at the ninety percent (90%) level ($R^2 = 0.826$).

Young-of-the-year abundance as determined when the population mean size was 1.4", 1.5", or 1.6" showed no significant relationship to striped bass recruitment when an n^{th} order polynomial fit was attempted.

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XI-A-43

SURFACE HEAT TRANSFER FROM A GEOTHERMALLY-HEATED LAKE

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ABSTRACT

A research investigation was conducted on a small geothermally-heated lake in Yellowstone National Park, Wyoming. The major goal of the experiment and analysis was to study the applicability of existing surface heat exchange theories in a somewhat extreme situation. Results may be used (i) to improve the prediction of temperatures near thermal discharges, (ii) to improve the prediction of heat dissipation, and (iii) for comparison with similar experimental studies or new theory.

The study establishes that the widely-used theory of Brady, Graves, and Geyer is applicable, but only within a framework of specific qualifications. Where the surface temperature Ts is significantly higher than the environmental equilibrium temperature E the theory should include everywhere the second order term $(Ts^2 - E^2)$. The windspeed function $f(W)$ determined in this study strongly corroborates both the parabolic form of the Brady, et al. function and the approximate value of $f(W)$ at $W = 0$. The differences at $W > 0$ suggest the necessity of field verification of the constants in the $f(W)$ function for any site. Lastly, the appropriate time interval over which the steady-state assumption of the theory is valid for a given field site must be established.

INTRODUCTION

Heat transfer prediction techniques have been based on the hypothesis that the capacity of a completely mixed lake to dissipate additional heat by surface cooling can be expressed as the product of a surface heat exchange coefficient K and the difference between the lake's actual surface temperature Ts (^oC) and its environmental temperature E (^oC). Relationships are generally derived from a simple energy balance; i.e., the rate of change of heat stored in a lake is equal to the rate of heat supplied to the lake less the rate of heat dissipated from the lake.

This hypothesis is justifiable on theoretical grounds, but its applicability to field situations is limited because one must first obtain valid values for K and E . A wide diversity of formulae exists for estimating the surface heat exchange coefficient K , and the method for estimating the equilibrium temperature E in terms of prevailing meteorological conditions is a complex sequence of successive approximations.

In order to simplify the procedure for K and E evaluation, the heat dissipation hypothesis can be applied in reverse. By first observing changes in heat storage within a lake, calculating actual prevailing values for K and E , and then correlating these with observed meteorological parameters working expressions for K and E can be derived. These simplified expressions can then be used to predict the surface heat exchange and surface temperature of a lake with a thermal discharge.

Theoretical and experimental investigations along these lines have been reported by Edinger and Geyer [1] , and Brady, Graves, and Geyer [2] . In order to evaluate their model in a somewhat extreme situation, the authors conducted a short term heat exchange research study on a geothermally-heated lake in Yellowstone Park.

THEORY OF HEAT EXCHANGE

The theory as given by Brady, et. al., [2] is briefly reviewed herein. For any water body with an extraneous heated inflow, the following expresses the balance of rates of heat exchange at the water surface.

$$Hst = Hrj + Hsn + Han - Hbr - He - Hc \qquad (1)$$

where Hst is the rate of change in heat storage, Hrj is the net rate of heat input, Hsn is the net solar radiation, Han is the net atmospheric radiation, Hbr is the back radiation, He is evaporation, and Hc is conduction. It has been established that

$$He = B(Ts - Td)\ f(W) \qquad (2)$$

$$B = (es - ea)\ /\ (Ts - Td) \qquad (3)$$

$$Hc = 0.47\ (Ts - Ta)\ f(W) \qquad (4)$$

$$Hbr = \sigma\epsilon\ \ (273 + Ts)^4 \qquad (5)$$

where es and ea are the saturated and dry air vapor pressures (mmHg), Ts, Td, and Ta are water surface, dewpoint, and air temperatures (^{o}C), σ is the Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2 - K^4$), ϵ is water emissivity (0.97), and f(W) is an empirical function of the windspeed (W/m^2 - mmHg). Upon expanding Equation (5) and neglecting terms of order higher than two, Equation (1) becomes

$$Hst = Hrj + Hsn + Han - (305 + 4.47\ Ts + 0.025\ Ts^2) - B(Ts - Td)f(W) - 0.47(Ts - Ta)f(W) \qquad (6)$$

The environmental equilibrium temperature E is defined as the water surface temperature at which, in the absence of an extraneous heat source, the rate of heat storage is zero, i.e., when Hrj = 0 and Hst = 0, then E = Ts. Substituting E and these conditions into Equation (6) and subtracting yields

$$Hst = Hrj + [4.47 + (B + 0.47)f(W)]\ (E - Ts) + 0.025(E^2 - Ts^2) \qquad (7)$$

Edinger and Geyer [1] have defined the terms in brackets in Equation (7) as the surface heat exchange coefficient K , i.e.,

$$K = 4.47 + (B + 0.47)f(W) \qquad (8)$$

These are the three components which approximately represent the relative contributions to the total dissipation arising from back-radiation, evaporation, and conduction, respectively.

Consideration of the energy balance on the lake indicates that the rate of heat supplied to the lake Hrj less the rate of heat stored in the lake Hst equals the rate of heat dissipated from the lake Hd. Therefore, the heat dissipation rate is given by

$$Hd = K(Ts - E) + 0.025(Ts^2 - E^2) \qquad (9)$$

When Ts approaches E , i.e., (Ts - E) is small, then the term $0.025(Ts^2 - E^2)$ is negligible and Hd becomes

$$Hd = K(Ts - E) \qquad (10)$$

Equation (9) is to be utilized for predictive purposes. Therefore, it is necessary to develop expressions for evaluating E in terms of known or measureable parameters. By solving Equations (6) and (8) for f(W) and equating the results, one obtains the following expression for K :

$$K = 4.47 + (Hrj + Hsn + Han - Hbr - Hst)/(Ts - Td^*) \qquad (11)$$

where Td* is

$$Td^* = Td + 0.47(Ta - Td)/(B + 0.47) \qquad (12)$$

Similarly, by solving Equations (6) (with Ts = E) and (8) for f(W), equating the results, and assuming $0.025\ E^2/K << E$, one obtains

$$E = E^* - (0.025\ E^{*2}/K) \qquad (13)$$

where E^* is

$$E^* = Td^* - ((305 + 4.47\ Td^*)/K) + (Hsn + Han)/K \qquad (14)$$

In Equation (14) the first term represents the equilibrium temperature which would prevail if the only active terms in the heat exchange balance were evaporation and conduction. The second term, which makes a negative contribution, represents the extent to which the equilibrium temperature would be depressed below Td^* if the process of back radiation joined evaporation and conduction in achieving the exchange balance. The third term represents the positive contribution of both solar and atmospheric radiation in completing the total radiation balance.

The following successive approximations can be made. Since the modified dewpoint temperature Td^* would normally be expected to exceed the true dewpoint temperature only slightly (Equation (12)) and the equilibrium temperature appoximation E^* would normally be expected to exceed the true equilibrium temperature by a similarly small margin, it follows that these small alterations tend to cancel each other in Equation (14) and lead to the approximation:

$$E = Td + Hsn/K + (Han - 305 - 4.47\ Td)/K \qquad (15)$$

The third term above contains components which tend to cancel one another. Furthermore, if the gross solar radiation Hs were substituted for the net solar radiation Hsn, the resulting additional contribution from this term might be sufficient to eliminate the need for the term involving Han altogether. Hence, the final approximate expression for the equilibrium temperature is given as:

$$E = Td + Hs/K \qquad (16)$$

In this approximation the equilibrium temperature is independent of water temperature except for the indirect influence of Ts on K. Equilibrium temperature by definition should also be independent of Hrj, but is not entirely, again because of the influence of Hrj on K. Under the assumption that these indirect influences are minor, Equation (16) may be utilized for predictive purposes and is used in [1] and [2] .

PREDICITION SCHEME DEVELOPMENT

Expressions for predicting the surface heat exchange coefficient K', equilibrium temperature E', and water surface temperature Ts' can be derived based on the theoretical model described above. The key to the predictive possibilities of the expressions is being able to relate the windspeed function $f(W)$, which is a function of the measured K value and not a direct function of windspeed, to a windspeed function $f(W)^*$, which is a function of the windspeed alone.

If a stable mass of warm air is lying over a body of cooler water, the air would be expected to inhibit the dissipation of heat by evaporation almost completely. However, if the air mass is significantly cooler than the water body, the air adjacent to the water surface becomes both warmer and more moist than that above it, thereby becoming less dense. Hence, much higher rates of heat and mass transfer from the water surface are expected due to the resulting vertical convective air currents. With the addition of a steady wind across the water surface, the accumulating moist air is continually replaced with fresh supplies of drier air. Also the shear stresses generated by friction between the air and water masses cause additional turbulent motion in the air. Both these phenomena increase the rates of heat and mass exchange at the water surface.

The dependence of surface heat exchange rates on windspeed has been the subject of several field evaluation studies. The results of five such studies [2] are shown in Figure 1 which indicates a wide range of values of $f(W)^*$ throughout the windspeed range, especially at low and high windspeeds. The discrepencies are attributable to (a) different averaging time period, (b) different measuring heights, (c) different local topography, and (d) variable evaporation, dewpoint, and surface temperature data quality. They also raise serious questions about the universality of the windspeed function and the soundness of its derivations.

The windspeed function $f(W)$ was calculated using the following rearrangement of Equation (8) :

$$f(W) = (K - 4.47)/(B + 0.47) \qquad (17)$$

By correlating calculated $f(W)$ values and observed windspeeds W, an expression can be obtained in the form:

$$f(W)^* = a_0 + a_1W + a_2W^2 + \dots \qquad (18)$$

This equation is a predictive expression for the windspeed function dependent only on windspeed. It is inconvenient to incorporate tabulated values of es and ea into a prediction scheme. By examining the relationship between T and B for known values, the following approximation for B was derived

$$B^* = 0.745 - 0.02754\ T + 0.00119\ T^2 \qquad (19)$$

where

$$T = (Ts + Td)/2 \qquad (20)$$

Equation (19) yields values very close to the observed values as computed by Equation (3). The predictive expression for the surface heat exchange coefficient was formulated from Equation (8), i.e.,

$$K' = 4.47 + (B^* + 0.47)f(W)^* \qquad (21)$$

Because this is the same expression which was used in evaluating $f(W)$ any differences between K and K' are only a reflection of the accuracy of the approximations for $f(W)^*$ and B^*, Equations (18) and (19) respectively.

Equation (16) was used as the predictive expression for the equilibrium temperature; thus,

$$E' = Td + Hs/K' \qquad (22)$$

where Td and Hs are measured and K' is the approximation discussed above. This expression not only reflects the approximations inherent in K', but also the successive approximations discussed in the development of Equation (16).

The predictive expression for the water surface temperature was derived first by solving Equation (7) for Ts in the following manner:

$$Ts' = (Hrj/K' - Hst/K' + E' + 0.025\,E'^2/K)(K'/(K' + 0.025\,Ts')) \qquad (23)$$

It is apparent that as Ts' appears on both sides of Equation (23), an iterative solution is necessary. The value for Hst is unknown, and is in fact a function of individual station surface temperatures at different times. Therefore, the actual value of Hst is the result of a field process which leads also to Ts and cannot be part of the prediction scheme. In order to be able to proceed a further simplification must be made. To satisfy this the steady state condition is assumed. This implies that heat storage ceases to change, i.e., $Hst = 0$. The predictive expression for the water surface temperature is now:

$$Ts'ss = (Hrj/K' + E' + 0.025\,E'^2/K')(K'/(K' + 0.025\,Ts'ss)) \qquad (24)$$

where Hrj is measured and K' and E' are approximations discussed above. This equation is not an approximate expression, but the predicted steady-state surface temperatures reflect the accuracy of the approximations for K' and E' and the approach to the steady-state condition.

SITE DESCRIPTION

This field study was conducted at Terrace Spring which is located in the west-central region of Yellowstone National Park, Wyoming. The small, natural lake has trees flanking the north and east sides and open space on the south and west. As a result a small portion of the lake is shaded in the early morning hours from direct solar radiation. However, the trees provide no shelter from the wind because the wind is almost always from the southwest.

A thermal spring is submerged in the far northeast arm of the lake and provides the only inflow. The high temperature at the spring is approximately 61(°C) while the low temperature at the far west end of the lake is around 41(°C). The south side of the lake is paralleled by the roadway under which a culvert carries all the outflow. In most areas the lake depth increases fairly uniformly to 1.5m between the shore and a distance about 75% of that to the center and then flattens out. The eight stations for water temperature measurements are shown in Figure 2. Meteorological measurements were made along the east and south banks. Other pertinent characteristics of the lake site are given in Table 1.

Because of the constant high flow rate, high water temperature, appropriate size and shape, and accessibility of the site, Terrace Spring was chosen for study. The one drawback of this site was its popularity as a tourist stop, for which reason the Park Rangers did not allow measuring equipment to be visible between 9 a.m. and 5 p.m. However, the large heat input (high flow at high temperature -- the highest in Yellowstone Park) was an advantage which was considered to outweigh this disadvantage.

DATA COLLECTION

The solar radiation Hs was measured using a MK I-G Sol-A-Meter silicon cell pyranometer. The output was read in millivolts on a portable potentiometer and converted to W/m^2. A sun dial apparatus which measured the length of a shadow was used for the sun's altitude angle. The wet and dry bulb temperatures were measured with a Bacharach sling pyschrometer. A rectangular section weir was installed periodically in the outflow channel to measure the flow rate. Van Water-Rogers Tele-Thermometer probes were utilized in obtaining the air temperature, the water surface temperatures, and the inlet and outlet temperatures. A digital gage thermometer, Digitec, from United Systems Corp., read the temperatures directly in degrees Celsius. The power source for this gage was an automobile battery with a Model No. 26-910 DC-AC transistorized inverter. The windspeeds were measured by a cup anemometer and a Wind Meter manufactured by Dwyer Control Gages. Precipitation, daily maximum and minimum air temperatures, and cloud conditions were recorded at two nearby weather stations. Measurements were taken in the early morning and/or late afternoon. Because the equipment could not remain at the site during the mid-day no lake-side continuous readings were taken. Each data collecting period required approximately one and a half hours. A pulley system which carried the thermister probe to the respective lake reading stations was set up for each of the eight stations. At each set up, in addition to the water surface temperature, the on-shore air temperature, wet and dry bulb temperatures, gross solar radiation, sun's angle, and windspeed were measured.

The first station, near the spring, was considered as the inlet; the remaining seven series of readings were used in obtaining average parameter values. For each 1 1/2 hour data collecting period the recorded Hs , Ta , Td (from the wet and dry bulb temperatures), and W are time averages of the seven respective readings and Ts is a time and space average. The outlet temperature and flow measurements were made approximately midway through the 1 1/2 hour period. Solar radiation, air temperature, dewpoint temperature, and windspeed were also checked during the day in order to obtain an integrated average for each 24 hour period.

In several instances a second data block was taken immediately after the first in order to observe changes over an approximate 2 hour time lapse. Occasionally a second block was observed that evening, approximately 12 hours after the first. Generally, data was gathered at 24 hour intervals, which thereby provide 48 hour and 168 hour (1 week) intervals.

The advantage of the short-term approach (2 hour and 12 hour) is to preserve the more accurate parameter integrated averages resulting from the higher concentration of readings. However, the main disadvantage arises from the high sensitivity to any larger-than-typical variations in the measured data and time functions on a given day. This occurs because 2 hour and 12 hour readings were not consistently made throughout the study. The longterm approach (1 week) tends to eliminate this disadvantage, but suffers the problem of significantly reducing the wide range of windspeeds, surface temperatures, etc. available for comparison with the computed values. The moderate-terms (24 hour and 48 hour) give the most meaningful results. Large atypical variations are partially smoothed, while the range of data remains significantly wide.

While the techniques and equipment used have respectable accuracies, the methods of obtaining time averages create a wider range of uncertainty. However, it is felt that in all cases the accuracies obtained are not inconsistent with this field situation and are sufficiently high to yield meaningful data.

The pyranometer employed for measuring gross solar radiation has a stated accuracy of ±5%. The final accuracy, however, is limited by the approximations involved in allowing for the variable effects of cloudiness and for the sun's angle. It is considered unlikely that this technique could achieve an accuracy better than about ±10%.

Individual values of air temperatures are considered to be accurate to within ±0.5(^{o}C). The wet and dry bulb readings are also considered to be accurate within ±0.5(^{o}C). However, the fact that tables were used for converting these readings to dewpoint temperatures increased this uncertainty to ±1(^{o}C). The accuracy for the 24 hourly representative observations for windspeed involves two factors. First, the instruments which were used have approximately ±5% accuracy. Second, the effect of a lower limit or "starting" windspeed for the anemometer tends to decrease the accuracy during low windspeed conditions. Taking these factors into account, it is considered unlikely that the windspeed data is more accurate than about ±10%. The thermal spring heat input accuracy is a two part consideration. The temperature of the flow is accurate to within ±0.25(°C) or better. However, the quantity of the flow can only be considered to be about ±5% accurate due to the difficulty in measuring the head above the weir crest H upon which the flow Q is dependent to the 3/2 power.

DATA REDUCTION

Net radiation is the sum of the gross (incoming) solar radiation, reflected solar radiation, gross atmospheric radiation, reflected atmospheric radiation, and back radiation. The gross solar radiation Hs was measured directly. Reflected solar radiation is obtained by multiplying the gross solar radiation by a reflectivity coefficient Rs which is a function of the amount of cloud cover and the sun's altitude angle.

Gross atmospheric radiation is a function of air temperature, air vapor pressure, dew point temperature, and cloud cover. Air vapor pressures were obtained from corresponding dewpoint temperatures which were derived from the measured wet and dry bulb temperatures. The reflectivity of atmospheric radiation is approximately 3% for a water surface, therefore the net atmospheric radiation Han is 0.97 Ha . Back radiation Hbr was evaluated using Equation (5) where Ts is the overall average surface temperature determined by multiplying each surface temperature measurement by a surface area weighted fraction and summing.

The change in heat storage within the lake Hst during any given time period, was computed using the formula:

$$Hst = (V\ D\ C_p/A) \sum_{i=1}^{n} Wvi(Ti_2 - Ti_1) \qquad (25)$$

where V is the lake volume (m^3), D is the density of water (kg/m^3), C_p is the specific heat of water (J/kg -°C), A is the lake surface area (m^2). Here, Wvi is the volume weighted fraction, Ti_2 is the temperature of the ith station at time t_2 , and Ti_1 is the temperature of the ith station at t_1. Heat rejected to the lake Hrj from the thermal spring was computed using the following expression:

$$Hrj = (Q\ C_p\ D/A)\ (Ti - To) \qquad (26)$$

where C_p, D, and A are as above, Q is the quantity of flow from the spring (m^3/sec.), Ti is the water temperature at the lake inlet and To is the outlet water temperature.

Field evaluation of the surface heat exchange coefficient was based on Equations (11), (12), and (3), in which all of the parameters, Hrj , Hr , Hbr , Hst , Ts , Td , Ta , es , and ea , were measured as field data or evaluated from field data. Equilibrium temperature E was determined from Equations (13) and (14) and the windspeed function f(W) from Equation (17).

Figure 3 is a plot of observed windspeeds versus calculated windspeed functions. Study of the data permits a fairly confident estimate to be made of the functional dependence of f(W) on W . In the absence of a multiple regression analysis on the data, the following expression for f(W)* (Equation (18)) is offered as representing a suitable combination of convenience and best fit:

$$f(W)^* = 9.9 + 0.66W^2 \tag{27}$$

Equation (27) provides for subsequent use of the windspeed function and hence the surface heat exchange coefficient in a predictive role. Figure 1 indicates how the curve of Equation (27) compares with other results.

Equations (21) and (22) respectively were used in calculating predicted values of K' and E' . Because several approximations were involved in the development of Equation (22), i.e., Equation (16), the accuracy was investigated by comparing observed equilibrium temperatures and approximated equilibrium temperatures. Using observed values of K in Equation (22) gives E** , i.e.,

$$E^{**} = Td + Hs/K \tag{28}$$

where all parameters are observed. Figure 4, a plot of E vs. E** , is an indication of the accuracy for the equilibrium temperature values. As the figure indicates, Equation (28) yields values very close to the observed values as computed by Equations (13) & (14).

With K' and E' values the predicted steady state surface temperature was determined using Equation (24). For the complete predictive scheme only four measured parameters, Hrj , Hs , Td , and W were required. The scheme involves first assuming a value for Ts'ss , utilizing this in Equation (20) to obtain T , and then proceeding as outlined below. The steady state predicted surface temperature is evaluated from Equation (24). This value is compared to the assumed Ts'ss and by iteration the true Ts'ss is computed. The predictive system of equations in summary form is thus:

$$T = (Ts'ss(trial) + Td)/2 \tag{20}$$

$$B^* = 0.745 - 0.02754\,T + 0.00119\,T^2 \tag{19}$$

$$f(W)^* = 9.9 + 0.66W^2 \tag{27}$$

$$K' = 4.47 + (B^* + 0.47)\,f(W)^* \tag{21}$$

$$E' = Td + Hs/K' \tag{22}$$

$$Ts'ss = (E' + Hrj/K' + 0.025\,E'^{2}/K')\,(K'/(K' + 0.025\,Ts'ss\ (trial))) \tag{24}$$

RESULTS

The K' results (24 hour data) were found to be within 5% of the K results. It should be emphasized the differences between K and K' are specifically attributable to the approximations for B* and f(W)* . Over the entire study period the average K' was only about 0.15% below K . The agreement of E and E' was within 5% everywhere and the overall study average of the prediction was about 0.5% below the observed value. The deviation here is nearly the same as was noted in Figure 4 which established the validity of the approximation for E . This observation indicates that the predicted values for K' seem to be accurate enough as to not alter significantly the prediction for E' .

Figure 5 indicates the time period at which the steady state assumption was acceptable. The ratio R2 is the average of Ts computed with the steady state assumption minus Ts computed without the steady state assumption over the steady state Ts . As R2 approaches zero steady state is approached. It is apparent that the 2 hour period and most probably the 12 hour period are not sufficiently close to steady state for the assumption to be valid. For the other periods the value of R2 indicates a less than one-half degree difference between the steady state and non-steady state temperature.

With predicted data and the steady state constraint, Equation (24) for Ts'ss yielded results which had a maximum deviation of 2.8% from measured values of Ts . The overall study average values differed by only 0.3% . Based on these results the conclusion is made that Equation (24) is useful and valid in predicting surface temperatures from data for time periods of 24 hours or greater.

In general application of the heat exchange theory Equation (10) is used for calculation of Hd . This expression was derived under the assumption that E approaches Ts . However, this assumption was not valid in this experiment and hence Equation (9) was used. In order to compare the results of making or not making this assumption, Figure 6 was plotted. The steady state approximation of the surface temperature without the assumption that (Ts - E) is small is derived from Equation (24) as:

$$Ts^{*}ss = (Hrj/K + E + 0.025\,E^{2}/K)(K/(K + 1.275)) \tag{29}$$

where E and K are measured values. The value 1.275 is the value of 0.025 Ts with an average Ts assumed to be 51(°C), a reasonable assumption for this study. The steady state surface temperature with the assumption that (Ts - E) is small is

$$Tsgss = E + Hrj/K \tag{30}$$

In Figure 6 R3 is the ratio of Ts*ss - Tsgss to Ts*ss. Therefore, as (Ts - E) becomes smaller, (Ts*ss - Tsgss) becomes smaller, and R3 becomes smaller. The lack of data for low values of (Ts - E) prohibits any precise judgement as to the R3 value below which the small (Ts - E) assumption is valid. However, a rough extrapolation of the trend is shown; R3 equal to 0.008 corresponds to a 0.5($^{\circ}$C)difference in temperature. Using this as a criteria (since the Ts accuracy is generally not any better than 0.5($^{\circ}$C))for the assumption's validity gives a (Ts - E) value of around 11($^{\circ}$C). Therefore, a gross approximation of 11($^{\circ}$C) is given as the temperature difference (Ts -E) below which the second term of Equation (9) can be neglected.

CONCLUSIONS

A major goal of the study was to investigate the theory of Brady, et.al., [2] under high water-temperature conditions. From the results obtained in the research this theory was found to be basically sound and useful with the following notable qualifications. Where the difference (Ts - E) is not negligible the theory should include everywhere the second order term ($Ts^2 - E^2$). A second qualification involves the selection of the windspeed function expression. The wide variation in experimental results indicates a possible nonuniversality for f(W) expressions and suggest that a location oriented evaluation may be necessary. Third, the form of the approximate expression B* used for the vapor pressure curve slope B was found to depend on the water surface temperature range. Results show that as the range increases the intercept term in the B* equation should increase. The fourth qualification is a reminder that the steady-state condition has been assumed and the physical parameter values must indeed show that this is being approached. A time period of approximately 24 hours was determined in the present study as a sufficient interval for the steady-state assumption to be valid.

The approximate expressions for the surface heat exchange coefficient and the equilibrium temperature given by Equations (8) and (16) were found to be sufficiently accurate for use in place of the complex expressions given by Equations (11) and (13).

The hypothesis of water surface heat exchange stated in the introduction was concluded to be a valid basis for temperature prediction. The net rate of heat exchange at a water surface may be estimated as a function of its surface heat exchange coefficient, its surface temperature, and its equilibrium temperature. This function is either in the form of Equation (9) or Equation (10) depending on the relative size of the second order term and/or the accuracy requirments.

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TABLE 1 - LAKE CHARACTERISTICS

Elevation above M.S.L.	2300 m
Elevation of Anemometer (above lake)	1.5 m
Lake Surface Area	2570 m^2
Lake Volume	2150 m^3
Lake Mean Depth	0.84 m
Lake Max. Depth	1.7 m
Lake Axial Length	110 m
Lake Inlet to Outlet Length	60 m
Average Inflow	5.6 m^3/min
Mean Flow-Through Time	3 hr
Mean Lake Surface per Station	320 m^2
Mean Lake Volume per Station	270 m^3
Summer Max. Air Temp.	32 ^oC
Summer Min. Air Temp.	-4 ^oC
Nearest USWB Station	25 Km

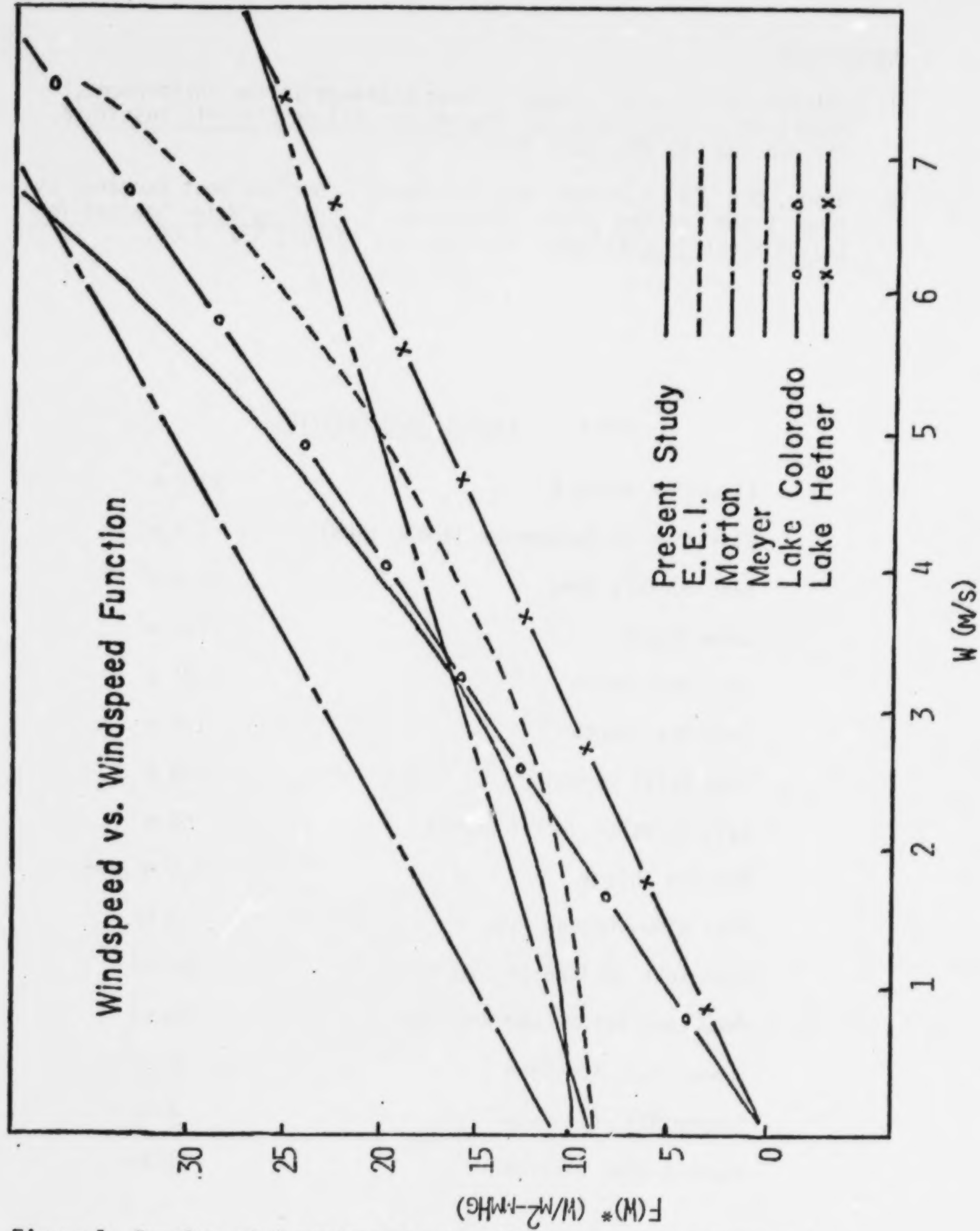

Figure 1. Results of 6 studies showing differences in windspeed vs. windspeed function relationships.

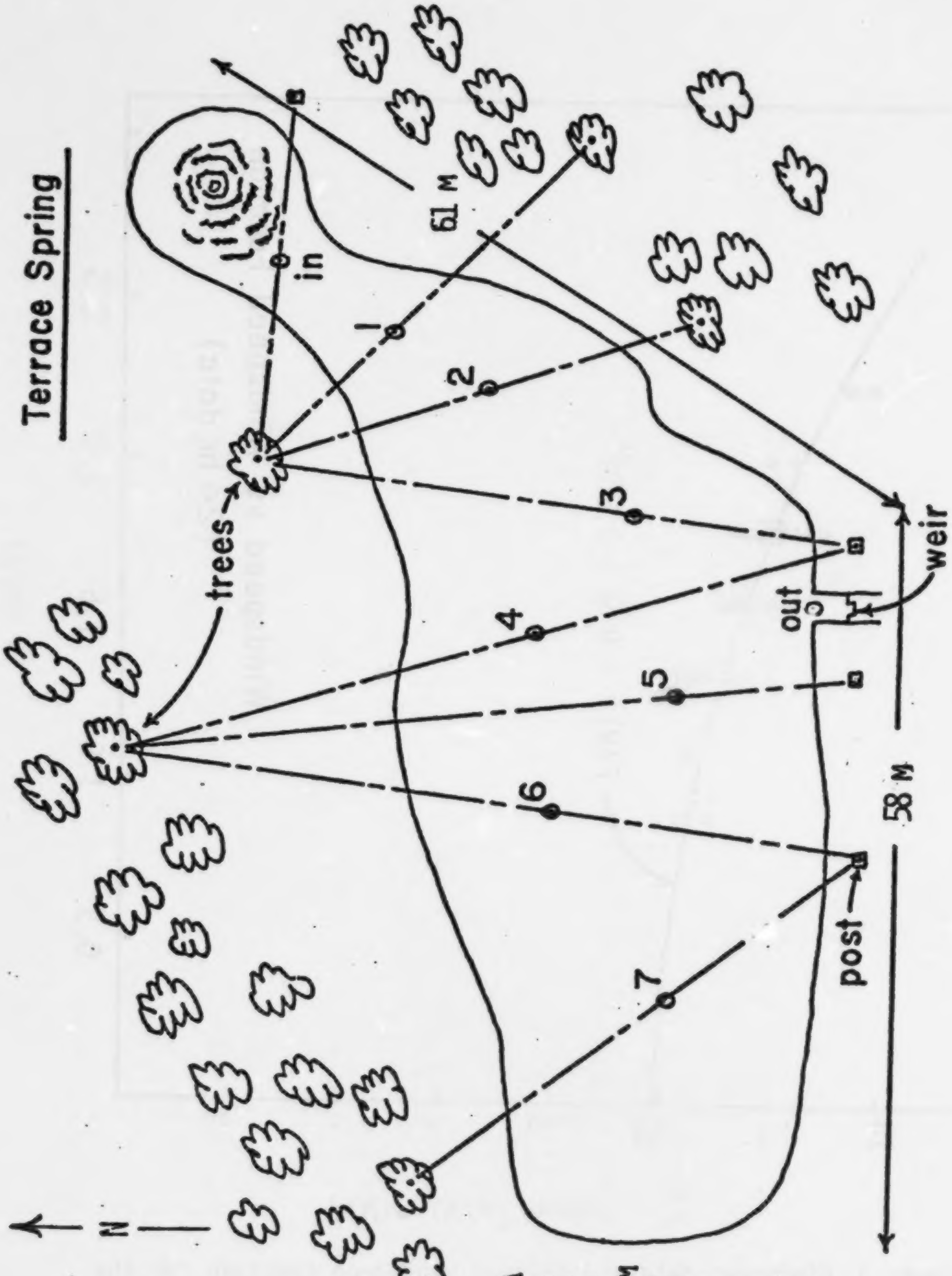
Terrace Spring
trees
in
1
2
3
4
5
6
7
61 M
weir
out
post
58 M
25 M
N

Figure 2 Schematic of Terrace Spring and sampling stations.

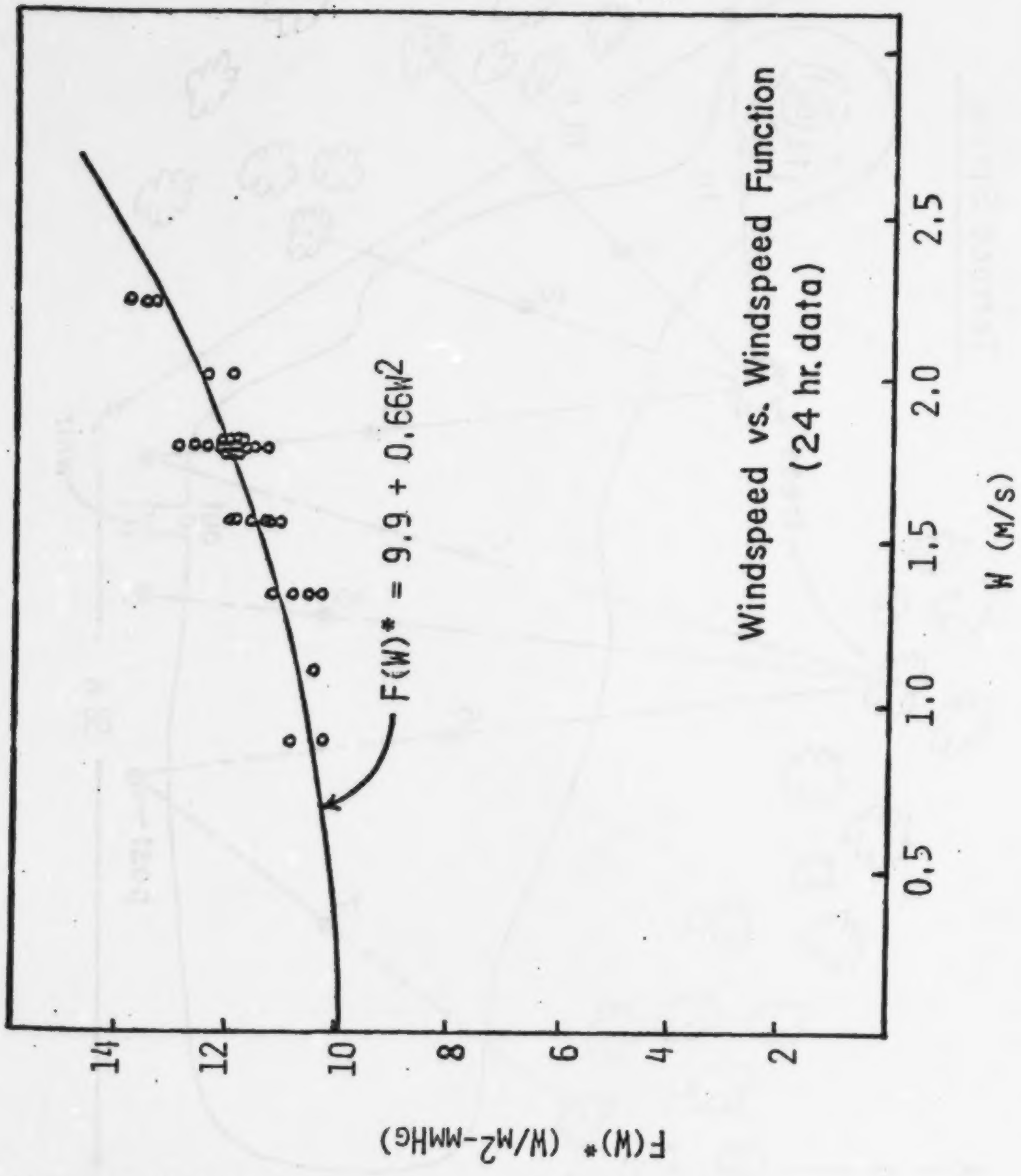

Figure 3 Windspeed data and derived windspeed function for the 24 hour time intervals of the study.

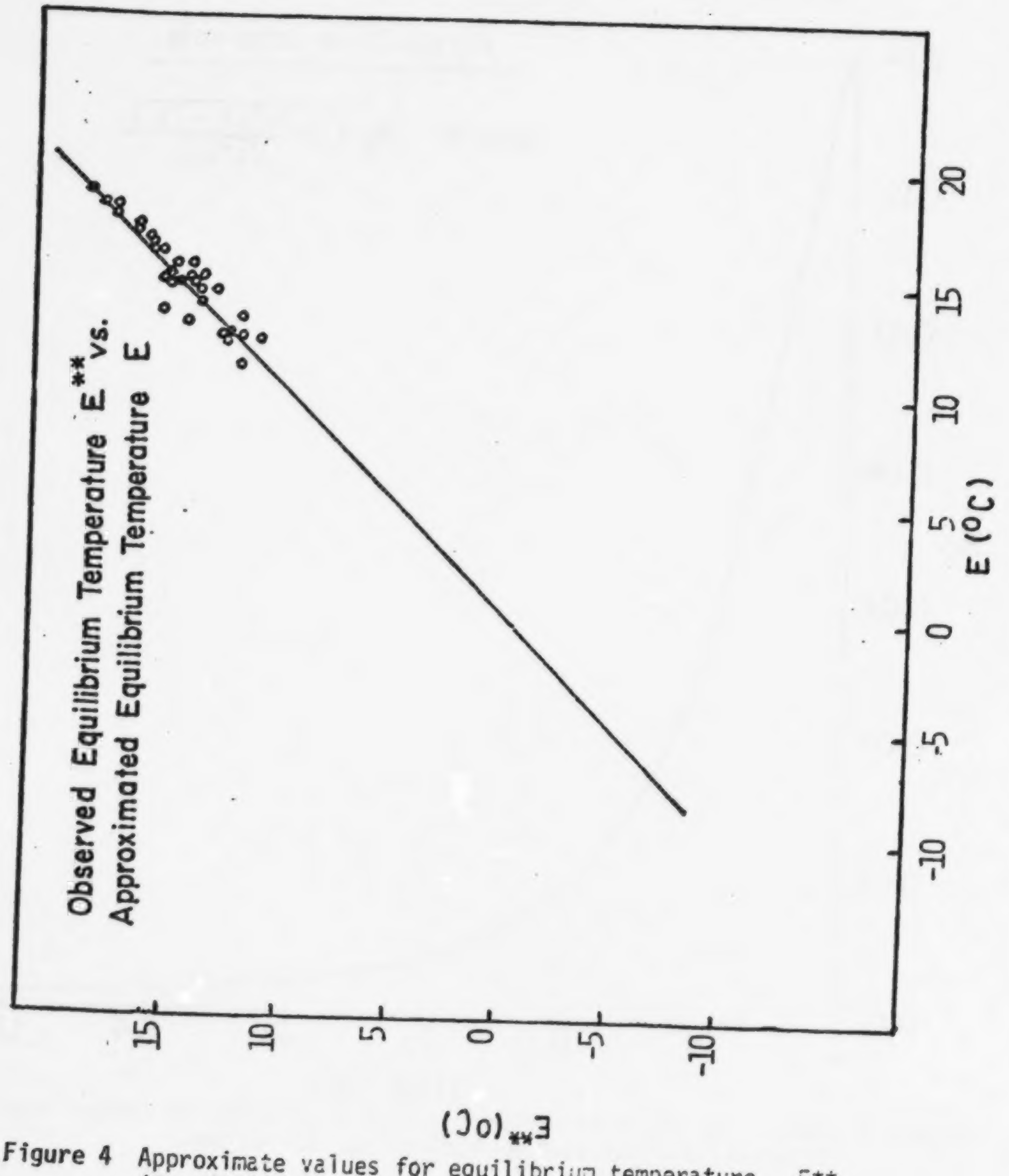

Figure 4 Approximate values for equilibrium temperature E** (Eq. (28)) are very close to observed values E (Eq. (13)).

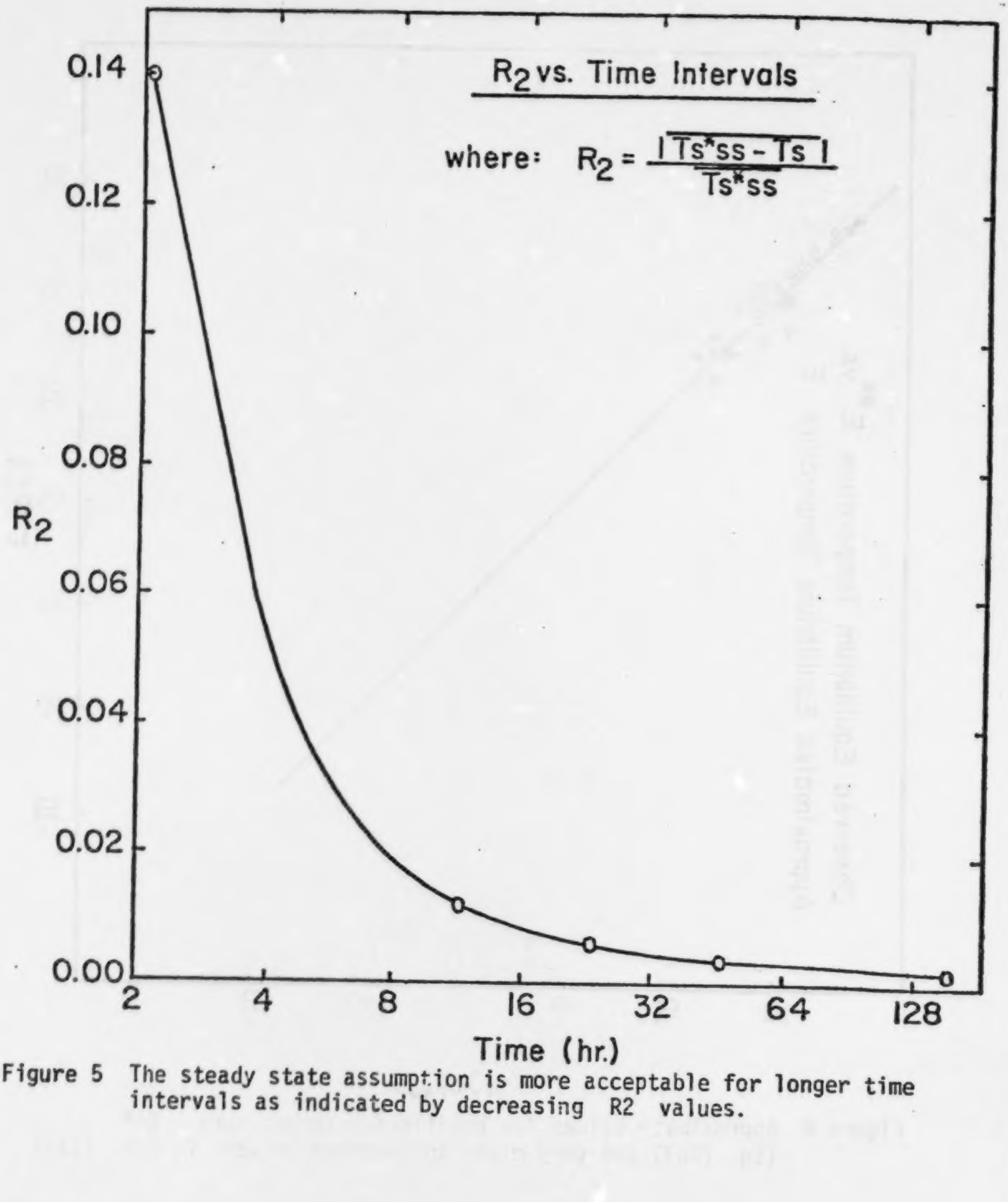

Figure 5 The steady state assumption is more acceptable for longer time intervals as indicated by decreasing R2 values.

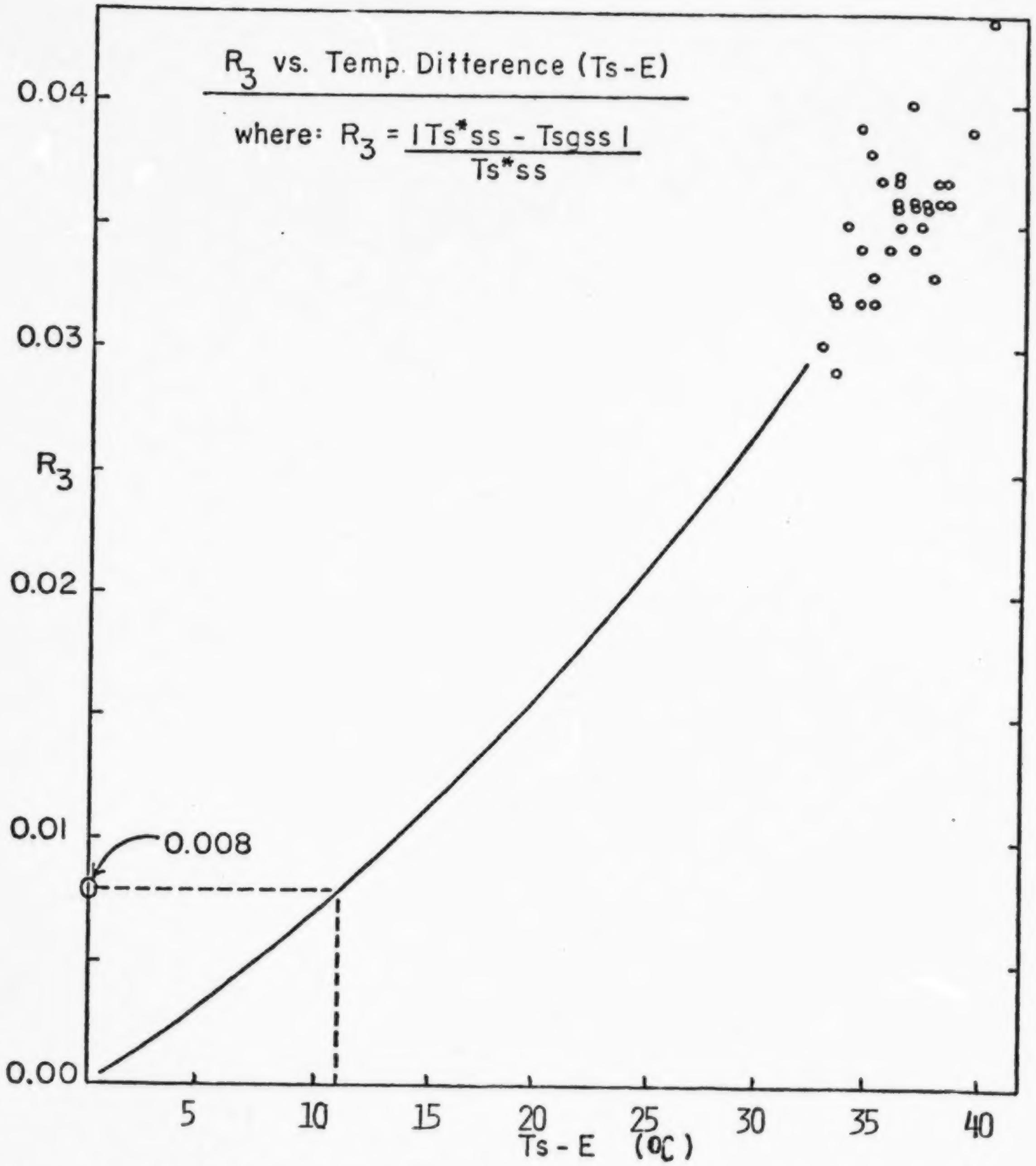

Figure 6 Elimination of the second order term in the heat dissipation calculation (Eq. (9) and (10)) is only acceptable when Ts - E is small as indicated by decreasing R3 values.

25-45-24

PATTERNS OF THERMAL PLUME CONFIGURATION: IMPLICATIONS FOR ENVIRONMENTAL IMPACT ASSESSMENT AND RESOURCE MANAGEMENT

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ABSTRACT

The major dimensions of configuration of thermal effluent plumes at numerous power plants with once-through cooling systems are discussed. Plume configuration patterns were characterized in the near field by temperature. Patterns of spatial-temporal variability are illustrated. While measured dimensions were site specific, a number of general configurational patterns emerged which were generally environment specific. Five major environment types and several subtypes were identified: (1) reservoir-pond (closed system); (2) impoundment (semi-closed); (3) flowing rivers (several subtypes-open); (4) estuaries (open); and (5) coastal/oceanic (open).

The biological-ecological implications of these patterns are briefly discussed in relation to observed or observable impacts to the resident biota and organisms vulnerable to direct impact. Closed systems of limited assimilative capacity appear most vulnerable to thermally induced changes in ecosystem state. Under present power plant siting strategies, cooling systems and capacity (<2000 MW), thermally lethal temperatures are seldom encountered and are very localized. Observed effects on local ecosystems appear difficult to detect against a background of large natural biotic variability. Thermal impacts at present appear generally quite restricted if detectable. Implications for power plant sitings as regulatory and resource management strategies are explored in regard to thermal addition to aquatic ecosystems.

INTRODUCTION

The accelerated use of natural waters for cooling purposes by power plants has been generally recognized as a potential contributor to the biological degradation of aquatic environments. This recognition has led to an extensive literature on thermal effluents at power plants, the biological consequences of thermal alteration to aquatic environments and regulatory/resource management philosophy (1,2,3,4,5,6,7). Much is known about temperature effects on various organisms, plant-induced thermal impacts to local environments and thermal plume modeling and configuration (8,9,10, 11). Furthermore, temperature criteria and standards have been promulgaded and various management strategies are now being employed by various regulatory agencies concerned with thermal impact. It is apparent however that concensus as to a consistent and scientifically defensible strategy for management of waste heat does not now exist. The subject of thermal additions remains a controversial issue to the scientific, industrial, legal and resource management sectors, and increased power demands, with attendant socio-economic implications, continue to exert strong pressure for expanded use of natural waters for cooling purposes.

The development of sound strategies for management of waste heat in aquatic environments must, in part, involve an assessment of the physical characteristics of thermal effluents as well as their potential subsequent environmental consequences (nature and extent of ecological changes). To this end configurations of thermal effluent plumes at numerous power plants having once-through cooling systems have been examined in relation to environmental setting. Certain implications for power plant siting, waste heat management, and thermal effects on the biota are explored. A number of conclusions, tentative hypotheses and recommendations are advanced in an effort to stimulate further development of managerial/regulatory policy consistent with national needs and goals.

THERMAL PLUME SURVEYS, METHODOLOGY AND CONFIGURATION PATTERNS

Pursuant to variance demonstrations under Public Law 92-500 (Section 316a) and for engineering considerations and model verification, Geo-Marine, Inc. has conducted numerous thermal surveys at power plants located in a wide variety of environmental settings (i.e., reservoirs/ponds, reservoirs/impoundments, rivers and estuaries). Some of these thermal studies have been in conjunction with biological studies, while others stand alone. The number of surveys at any given location have varied considerably and many sites have been examined under markedly different thermal and water flow regimes.

Both the areal and vertical extent of thermal plumes have been defined by towing a series of fast response thermistors in the receiving water body and digitally recording simultaneously both temperature and positional information (12). The method allows large amounts of data to be obtained in a short period of time, an essential element in accurate thermal plume description. Dissolved oxygen measurements within the thermal plume have also been measured using the same techniques.

The major physical processes determining plume configuration are well known, have been an integral part of mathematical models of thermal effluents and will not be discussed in detail here. The dynamics of heat dissipation in receiving waters are a function of factors controlling water motion as well as the total surface area exposed to atmospheric interchange. An examination of a large number of thermal plume surveys made by Geo-Marine, Inc. revealed certain patterns in the distribution of heated water from power plant discharges which in varying degrees can be attributed to specific environmental settings. In each of these settings, the determinants of heat dissipation are usually sufficiently distinct to enable them to be discussed as separate categories.

Reservoirs/Ponds

This category generally includes bodies of water of limited size and tributary flow. Many are specially created to act as a cooling water source for power plants and often exhibit lower heat assimilative capacity than larger systems. Biological communities are generally closed, i.e., have limited contact or connection with sources of disseminules (*sensu* Cairns (11)) from adjacent aquatic environments.

Figure 1 descirbes the distribution of temperature in a cooling pond built specifically to provide cooling water. The pond has an area of 2000 acres and an average depth of approximately 15 feet (40 feet maximum). Three thermal surveys were completed; a pre-operational survey, one with a single 600 MW unit at full load, and another with two units at full load (1200 MW). Both thermal and dissolved oxygen measurements were taken simultaneously. Table 1 shows plant load data along with meteorological conditions (wind speed and direction were similar for all three surveys).

Figure 1 shows the temperature distribution at the near-surface and at the 10-foot depth for the three surveys. A cross-section of temperature and dissolved oxygen was constructed from data measured along the axis of the pond. Under single load conditions, thermal alteration was confined to the shallow discharge embayment. By doubling the load, both sides of the lake were thermally altered and more extensive heating at 10-feet was recorded. Major points of interest are: the extent of areal coverage of heated water compared to that available, the limited penetration of heated water across density gradients, and particularly the significant lowering of the thermocline under additional unit load. As dissolved oxygen profiles remained the same throughout the three surveys, adding the second unit resulted in cooler water being located in dissolved oxygen depauperate water. This could, for instance, significantly affect certain fish species using the thermocline as a refuge area.

Reservoirs/Impoundments

These systems exhibit transitional characteristics between the closed pond and continuous flowing riverine systems. Biologically there is a source fauna and flora present from the stream prior to impoundment (sometimes augmented by introduced species) and these systems usually have access to dimmeninules from tributary or contiguous environments. Often there is considerable seasonal variation in flow and heat assimilative capacity varies widely. Impoundments can exhibit thermal stratification and/or oxygen depletion at certain seasons.

Two examples were chosen that typify thermal discharge in reservoirs/impoundments. The first is from a site with a survey area of approximately 5800 acres. The power plant has a generation capacity of approximately 885 MW with an intake water pump rate of 1700 cfs. Two surveys were chosen to illustrate high and low river throughflows. Table 2 lists plant generation, meteorological data and throughflows.

Figure 2 shows the isotherm configuration for the near-surface and at nine feet for both surveys. The data clearly demonstrate that the plume pattern is mainly dominated by the flow, although under certain low flow conditions, wind can be a dominant factor. Dissolved oxygen was measured in all surveys and values ranged from saturation levels (>8.0 ppm) at the surface to approximately 5.0 ppm at the nine-foot depth.

The second example (Figure 3) illustrates diel effects on thermal plumes. Two surveys were completed on the same day; one in the early morning and one at mid-afternoon. The plant load was in the 670 MW range and had been at that range for 12 hours prior to the surveys. Figure 3 depicts the isotherms at the near-surface and at nine feet. Table 3 shows the plant generation and meteorological data during the surveys.

The effect of solar radiation resulted in a change in the temperature of ambient waters, with a 3°F rise between the morning and afternoon surveys. The plume and thermal structure at nine feet were not affected greatly, but some extension in the far field can be seen.

Of particular interest with reservoir/impoundments is the effect of water flow in the reservoir on surface plume configuration. At higher flows, the mixing zone is localized and the plume irregularly shaped and limited in areal extent. At low flows, a considerable area above ambient surface temperatures can be detected. Generally, at both the high and low flows, the plume is confined to the surface with dissolved oxygen values often remaining well above 5 ppm within the thermal plume. Thermal plume configurations in impoundments vary with flow, and the ratio of surface area of detectable thermal influence to available surface area is a function of thermal additions, pump rates and impoundment size.

Flowing Rivers

Three distinct types of riverine systems were identified; one in which flow direction is constant, one in which flow direction is constant at certain seasons but with little to no flow during other seasons, and finally, rivers in which tidal influences result in temporarily variable direction of flow.

Figure 4 shows the near-surface and 10-foot isotherms of a thermal plume in a continuous flowing river, during low flows and high ambient temperatures. Plant generation during the survey averaged 1660 MW and the heated water was discharged through a surface discharge. The surface plume dissipates rapidly (approximately 7000 feet) and reaches beyond mid-channel. At a depth of 10 feet, the plume is considerably reduced in extent. For rivers with large volume, high flow rates (e.g., Missouri River), thermal plumes tend to be severely restricted to the near bank.

The results of two surveys were chosen which characterize thermal plumes in a river under varying flows (Figure 5). In this case the river is narrow and highly channelized. Table 4 shows plant generation, meteorological data and throughflows for both surveys.

The discharge during the autumn survey was slightly below the surface of the water whereas in the summer survey the discharge was at the surface. Figure 5 shows the near-surface and 12-foot depth isotherms for both surveys. The autumn surface plume extends bank to bank immediately downstream of the discharge and continues to the end of the survey where it is within 1°F of ambient. At the 12-foot depth the heated water dissipates rapidly to 1°F of ambient immediately downstream of the discharge. During the summer survey the river exhibited characteristics associated with closed canals with low flow rates, vertical stratification and high ambient temperatures. Recirculation was occurring and among the dominant influences on plume configuration were wind, pump rate and temperature rise through the plant. Heat was not as rapidly dissipated. Low flow and the limited area for atmospheric interchange appear to be the major contributors to the observed rates of heat loss.

Two thermal plumes in rivers under tidal influence were chosen to illustrate: (1) a discharge located in an area of low tidal height but marked salinity gradient (salinity wedge), and (2) a discharge located in an area of high tidal heights. Figure 6 illustrates isotherm configuration at various depths for both tidal cycles. Table 5 lists meteorological and plant generation data. This particular riverine system is characterized by a strong salinity gradient with a thin layer of freshwater overlying higher salinity water. As can be seen in Figure 6, the thermal plume sinks or dives with warmer more saline water foundat 2-4 feet. By a depth of seven feet, little heating can be detected. The effect of tide stage is apparent in determining plume configuration at intermediate depths. Another point of interest is the apparent ineffectiveness of vertical heat transfer processes with the result being an extensive thermal plume at intermediate depths.

A riverine discharge into source waters with high tide amplitude is illustrated in Figure 7. Here the plume is surface limited and obviously dominated by tidal influences. Heat is rapidly dissipated and plume configuration changes markedly with tidal stage.

In summary for riverine settings, configuration is highly correlaged with river flow. With a continuous flowing river, plumes are offset downstream, rapidly mixed and limited primarily to the surface waters. It should be noted that with high flowing rivers like the Missouri, the thermal plume is rapidly mixed, not limited to the surface, and remains contiguous to the discharge bank (12,13). On rivers with low flow, parameters other than flow can dominate and heat dissipation is often much more limited. For tidally influenced rivers, plume configuration is a function of salinity and tidal flows, and is therefore quite unstable temporarily. Heat assimilative capacity of riverine systems is often high and the extent of detectable thermal influence is generally limited to a few miles at most plant sites even under conditions of low flow.

Estuaries

This environmental setting is characterized by tidally influenced water movement and meteorological conditions which often exert a dominant influence on plume configuration. These plumes are generally unstable in configuration and heat is rapidly dissipated. Estuaries are generally shallow and thermal mixing zones often reach the bottom. Figure 8 depicts near-surface isotherms of flood and ebb tide surveys at a discharge during two different season periods. Table 6 shows the plant load and meteorological data for each survey. Although the water depths are not shown in the figures, most of the heated waters lie between the shoreline and the 2-foot depth contour. At the 6-foot contour line, temperatures are within 1°F of ambient.

A more confined estuary into which heated waters are being discharged was also surveyed during flood and ebb tides (Figure 9). The discharge area is also very shallow (two feet maximum depth) and only near-surface data could be obtained. Table 7 shows plant load and meteorological data. Both surveys were completed on the same day. Again tidal influences are apparent and heat is rapidly dissipated.

Coastal/Oceanic

Effluent plumes of heated water at coastal sites are similar to those of large lakes or impoundments in certain respects and are not illustrated here. Wind, tide and coastal currents however contribute to high water motion and therefore rapid heat dissipation. Plume configurations appear highly variable and generally limited to surface water.

DISCUSSION AND CONCLUSIONS

Physical

A number of observations and conclusions relevant to waste heat management and assessment of environmental impact arise from a consideration of patterns of plume configuration associated with thermal effluents. While many of these observations are not unique or novel and many have been discussed elsewhere, they are nevertheless important in impact evaluation and the development of thermal regulation/managerial strategies and need be put in an overview perspective.

It is immediately apparent that each aquatic environment has a unique thermal structure, characteristics of water motion, bathymetry, temporal variability of ambient temperature and overall surface area or size. It is also evident that the general characteristics of plume configuration can be predicted from a knowledge of a few parameters. In this regard vertical dissipation of heat is much less important than atmospheric interchange and mixing or entrainment processes in the receiving water body. Of particular interest here is the dependency of plume configuration on environmental setting where one or two of the parameters determining rates of heat dissipation are usually dominant. The extent of thermal alteration to aquatic environments at a given plant is a function of pump rate, temperature differential and most importantly the heat assimilative capacity of receiving waters. Point source discharges at most plant sites have small mixing zones compared to the absolute size of the receiving system (i.e., river, lake, estuary) and in many cases plumes are quite localized in extent (14). Subsurface diffusers and other effluent designs for increasing mixing and heat loss appear effective in reducing plume sizes and the areal extent of thermal plumes.

Several additional observations are relevant to evaluating environmental impact. Thermal plumes are primarily surface phenomena seldom directly affecting deep waters or extensive areas of benthic habitat. Heated water reaches shallow benthic habitats most commonly at estuarine and coastal sites. Large stochastic components effecting plume configuration (e.g., plant load, flow, wind, currents) generally result in reduced mixing zones and less thermal alteration of receiving waters than predicted by models which assume idealized, often worst-case conditions. Indeed, worst-case conditions are seldom encountered and are usually of short duration. In the temperate U.S. these generally occur at times when resident biotas must contend with high ambient temperatures and reproductive activity is low. Incipient lethal temperatures are seldom reached for most indigenous organisms and when they do occur the areal extent of the lethal mixing zone is quite limited. The time/temperature history of a geographic point subject to above ambient temperatures, particularly in the far field, is highly variable. Where tidal motion is important to receiving waters, high variability in plume configuration and location is evident with rapid heat loss and smaller mixing zones. From a consideration of heat dissipation, tidal riverine settings are extremely attractive sites for thermal discharges.

Biological and Regulatory Considerations

An extensive literature now exists on the effects of temperature on organisms and biological systems at many levels of organization. The biota in the vicinity of thermal effuents has also received considerable study (15,16,17). A more extensive discussion of biological effects will be the subject of another paper and the intent here is to review certain very general observations stemming from biological studies at power plants. When coupled with the physical considerations and present regulatory policy, certain conclusions and tentative hypotheses relevant to waste heat management can be made.

Waste heat behaves differently from dissolved or suspended contaminants in several important respects. Heat does not generally effect water quality for human consumption or other uses (domestic, industrial, recreational, etc.). Aquatic systems have high heat assimilative capacity and the rapid dissipation of heat limits the area potentially impacted by thermal effluents. Only organisms which occur in the vicinity of a plant are vulnerable to direct or indirect (primarily through impingement/entrainment of organisms) effects. Of the set of species present, a substantially smaller subset can usually be shown to be effected. While conceivably mortality at a plant site could have repercussions far from that location (e.g., mortality to fish populations), significant impacts from waste heat have not been documented far from the area of discharge as have many biologically active chemical contaminants. Ecosystems and environmental settings are unique with regard to heat assimilative capacity, ambient temperature regimes and resident biota. The magnitude of potential ecosystem state (sensu Webster (18)) changes are a function of system scale relative to thermal alteration. Systems with a high habitat redundancy ratio (the ratio of area unaffected, but similar in system structure and function to the impacted area prior to thermal addition, to that impacted by a point source) are less likely to exhibit major state changes for a given thermal addition. Based on present plant designs and effluent limitations, significant deterioration based on routine monitoring of ecosystem structure or function cannot now be substantiated for large open-ended systems (e.g., large rivers, lakes, estuaries). "Thermal blockage" as presently defined and observed does not generally represent a lethal condition nor does it appear effective in blocking or reducing the number of migrating forms which pass a plant site. Mortality associated with indirect effects (e.g., entrainment/impingement) has not been shown to cause detectable changes in resident populations except on possibly a very local scale. Where more sophisticated techniques have been used, they have substantiated the "no effect" conclusion (11). Estuarine and coastal thermal discharges which are located on large bodies of water appear to have little detectable effects on local ecosystems except in the immediate vicinity of the discharge site. Habitat redundancy and environmental heterogeneity in conjunction with high variability in natural populations, their large size and apparent compensatory ability to thermally induced effects. Long-term changes in ecosystem state can presently only be detected by continuous monitoring of a broad spectrum of resident organisms and available habitat, an observation of critical importance to environmental management.

The inability to document significant deterioration due to thermal addition at many sites renders present regulatory policy (e.g., offstream cooling) legally vulnerable. Temperature standards, while scientifically defensible with regard to whole systems or populations, are difficult to assess or defend when applied to a single site. Environmental managers are often placed in a position where a course of action other than the granting of a variance cannot be substantiated based on the current data base. Subsequent ligitation in the event a variance is not granted may result in placing the burden of judgement as to significant deterioration on the judiciary. This seriously weakens the ability of the regulatory agency to manage the environment and more importantly, places an inordinate burden of responsibility on the legal system in addressing a highly technical and complex issue. Furthermore, there is no widely accepted criteria for judging what constitutes significant deterioration or acceptable impact. The determination in any instance is based on the subjective judgement of the manager having jurisdiction in addition to which there are often numerous agencies which have jurisdiction at a particular site.

Implications for Waste Heat Management

It is apparent that severe impacts from cooling water systems have not materialized and that in most environments, under present design criteria, little impact can be detected by presently available techniques. An assessment of the cumulative effects of thermal addition to a given environment at multiple sites is an exceedingly difficult task and the required information and problems associated with obtaining it have been discussed elsewhere (7, 19,11, and others). These problems must be addressed, however, and the requisite predictive capability developed.

There are, of course, finite limits to the number of cooling systems which can be added to any given system before detectable changes in ecosystem state are observed. Given the present state of knowledge, the question for management is how best to proceed while improved predictive capability is being achieved. The promulgation of categorical remedies (e.g., offstream cooling) while relieving the management sector of further responsibility begs the issue and impedes further progress to the development of policy leading to efficient utilization of limited resources. Certain predictions of a general nature can be made from a consideration of the environmental setting, plant operating characteristics and resident biota which are reliable as to the general nature of prospective impact.

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In conclusion, the present utilization of aquatic resources for cooling purposes has not generally been shown to produce unacceptable ecosystem states and minimally present levels of use can probably be maintained indefinitely. For many aquatic systems, considerable expansion of utilization for waste heat purposes is likely possible without producing unacceptable ecosystem states. By using what is known about the configuration and extent of thermal plumes in relation to environmental setting, and a general knowledge of the biological characteristics of the receiving system, utilization might be substantially increased by judicious site selection alone. A responsible management strategy must include continuous updating and dissemination of information relevant to assessment, prediction and decision making. The economic consequences of present and future demands on natural resources make it imperative that we implement management strategies which most efficiently utilize these resources while maintaining acceptable ecosystem states.

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Table 1.
Plant Load and Meteorological Data
(Figure 1)

	Date	Air Temperature (°F)	Plant Load (MW)	Time
Pre-Operational, Survey 1	31 July 1975	85	0	1202-1418
One Unit Load, Survey 2	11 August 1975	94	580	1238-1529
Two Unit Load, Survey 3	6 August 1976	96	1200	1237-1513

Table 2.
Auxiliary Data
(Figure 2)

	Plant Generation (MW)	Wind Direction (Degrees)	Wind Speed (kts)	Air Temperature (°F)	Throughflow (cfs)
Winter High Flow	870	90	6	58	49,000
Summer Low Flow	780	188	8	92	20,000

Table 3.
Plant Generation and Meteorological Data
(Figure 3)

	Plant Generation (MW)	Wind Speed (kts)	Wind Direction (Degrees)	Air Temperature (°F)
Early Morning Thermal Survey	672	4	200	82
Mid-Afternoon Thermal Survey	670	10	175	96

Table 4.

Plant Generation, Meteorological and Throughflow Data (Figure 5)

	Plant Generation (MW)	Wind Speed (kts)	Wind Direction (Degrees)	Air Temperature (°F)	Flows (cfs)
Survey 1 (Autumn)	235	6	30	50	5770
Survey 2 (Summer)	126	16	180	85	842

Table 5.

Meteorological and Plant Generation Dtaa (Figure 6)

	Air Temperature (°F)	Wind Speed (kts)	Wind Direction (Degrees)	Plant Load (MW)
Survey 1 (Flood Tide)	91	0	60	246
Survey 2 (Ebb Tide)	91	6	80	245

Table 6.

Plant Load and Meteorological Data
(Figure 8)

	Time	Air Temperature (°F)	Wind Speed (kts)	Wind Direction (Degrees)	Plant Load (MW)
Survey 1, Flood Tide 5 July 1973	1118-1247	94	13	240	356
Survey 2, Ebb Tide 6 July 1973	1552-1742	84	10	250	353
Survey 3, Flood Tide 22 November 1975	1422-1658	54	12	300	343
Survey 4, Ebb Tide 22 November 1975	1046-1310	49	10	330	344

Table 7.

Plant Load and Meteorological Data
(Figure 9)

	Time	Air Temperature (°F)	Wind Speed (kts)	Wind Direction (Degrees)	Plant Load (MW)
Survey 1, Flood Tide 18 September 1975	1313-1429	85	3	360	298
Survey 2, Ebb Tide 18 September 1975	1835-1940	80	0	45	242

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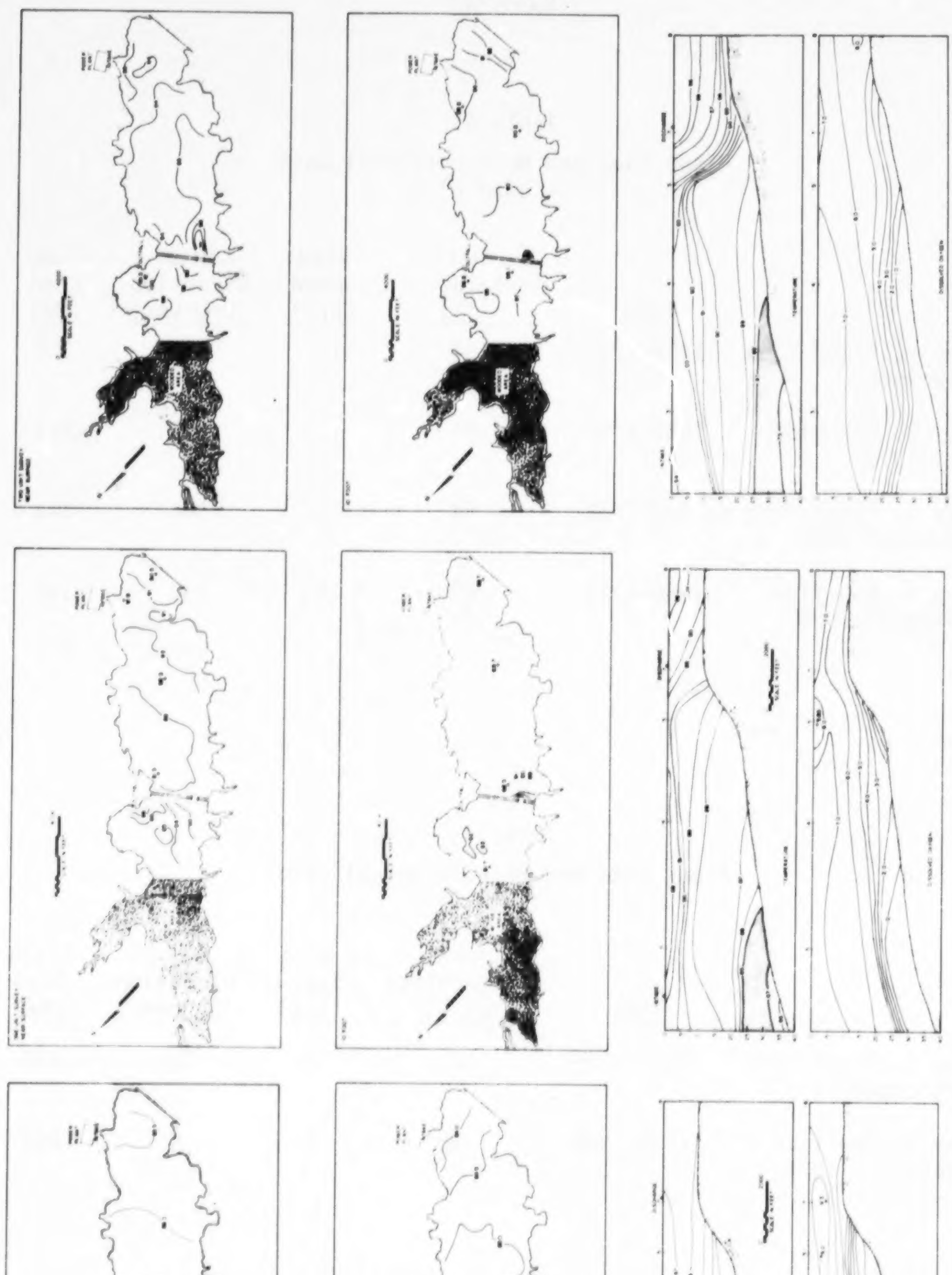
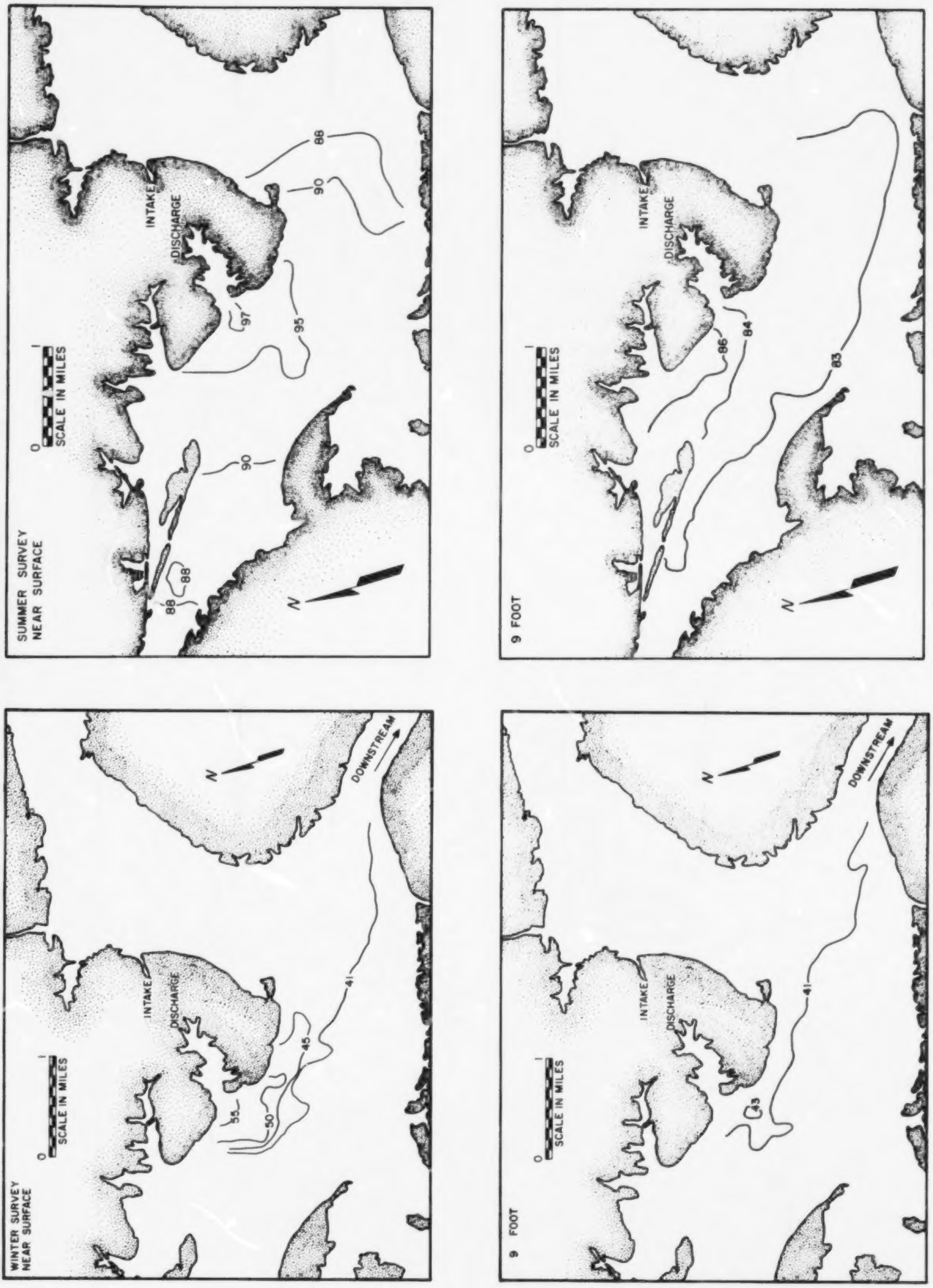


Figure 1. Reservoir/pond temperature distribution for three surveys.


SUMMER SURVEY
NEAR SURFACE
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SCALE IN MILES
INTAKE
DISCHARGE
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97
95
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88
88
88
N
9 FOOT
86
84
83
WINTER SURVEY
NEAR SURFACE
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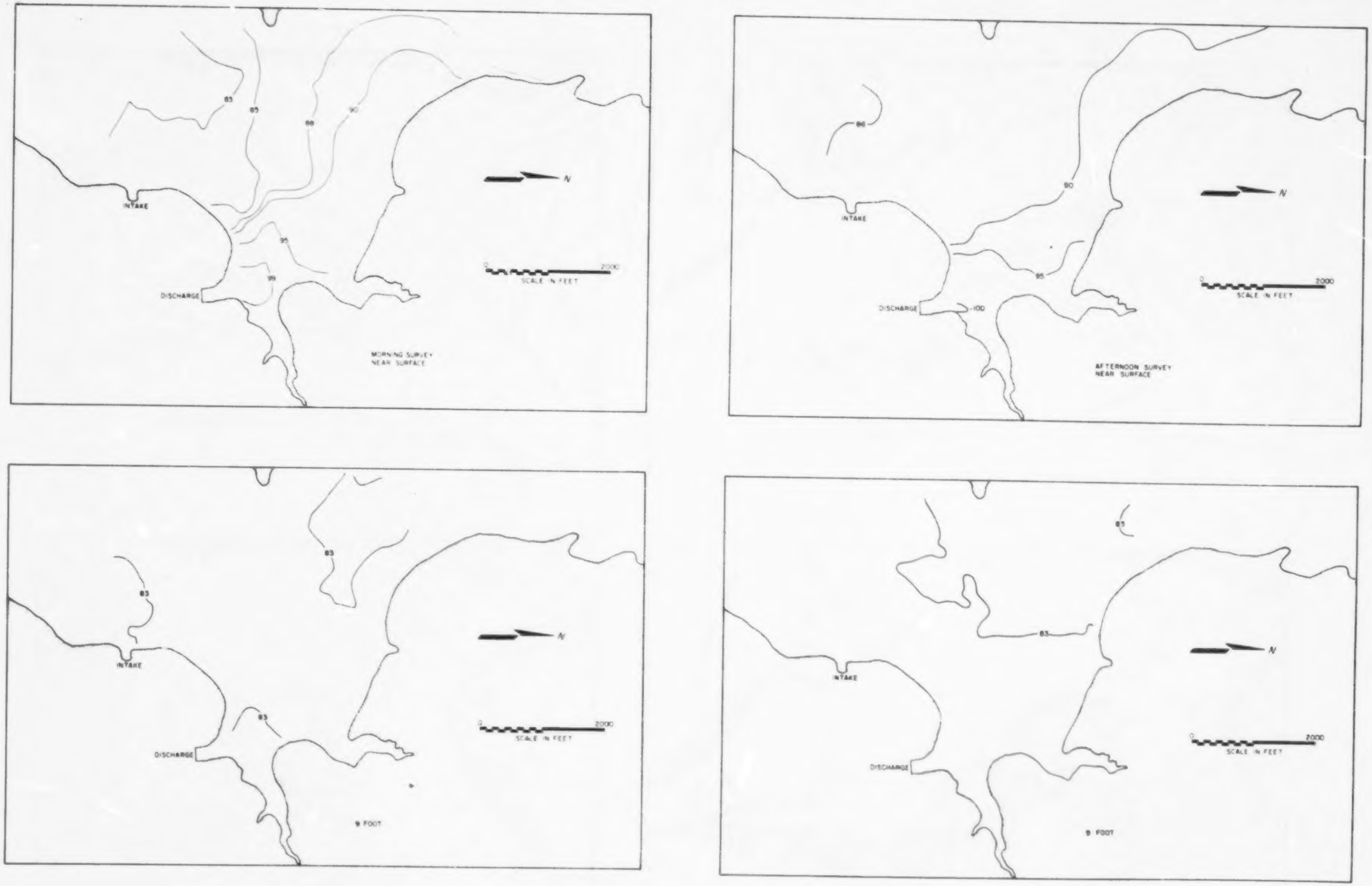
50
45
41
DOWNSTREAM
9 FOOT
43
41

Figure 2. Reservoir/impoundment temperature surveys.


83
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INTAKE
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SCALE IN FEET
MORNING SURVEY
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9 FOOT

Figure 3. Reservoir/impoundment diel thermal surveys.

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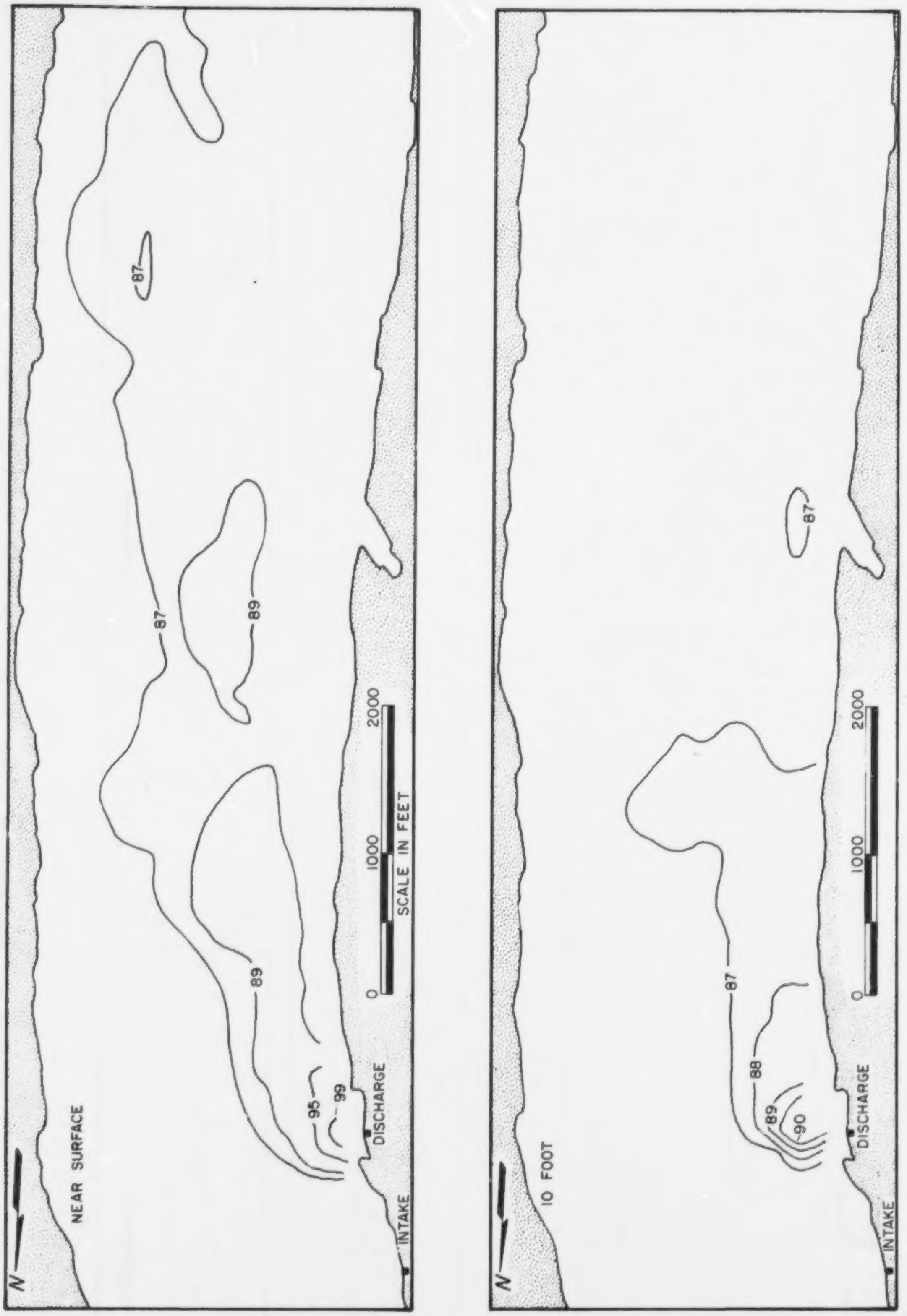
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0
1000
2000
10 FOOT
N
INTAKE
DISCHARGE
90
89
88
87
87
0
1000
2000

Figure 4. Temperature survey for a constant flowing river.

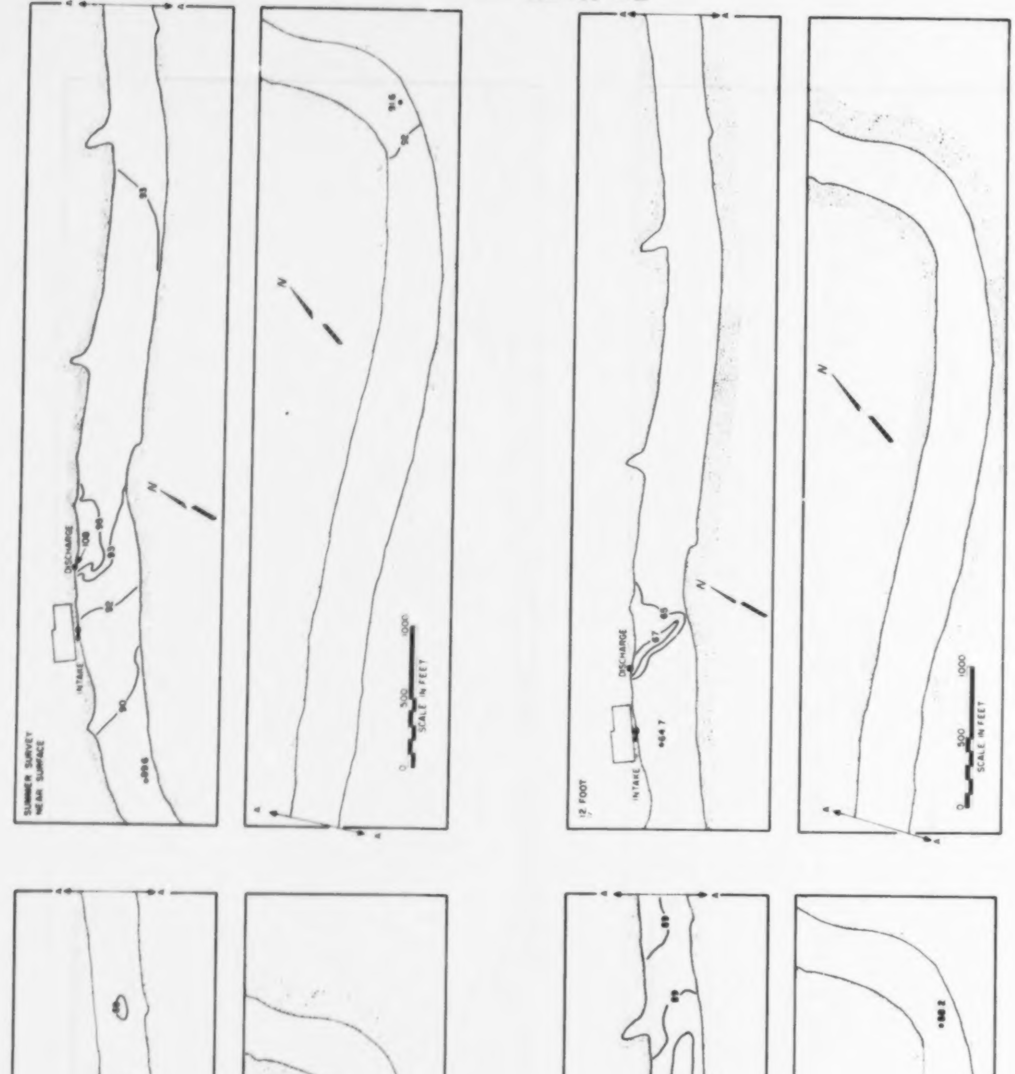
SUMMER SURVEY
NEAR SURFACE
AUTUMN SURVEY
NEAR SURFACE
12 FOOT
12 FOOT
INTAKE
DISCHARGE
N
SCALE IN FEET
0
500
1000
A

Figure 5. Temperature survey in a river with varying flows.

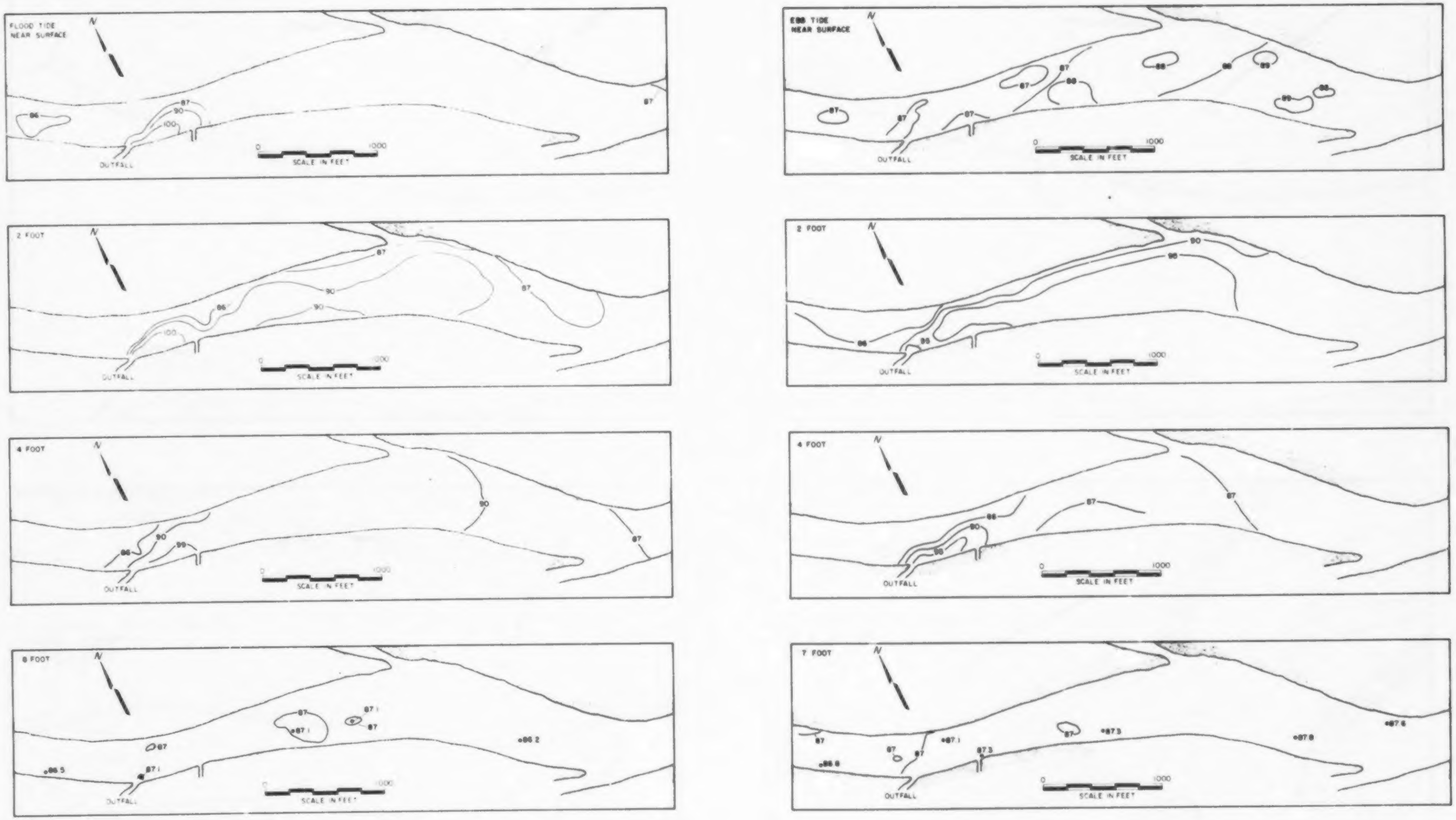
FLOOD TIDE
NEAR SURFACE
N
87
90
100
86
OUTFALL
0
1000
SCALE IN FEET
EBB TIDE
NEAR SURFACE
87
88
89
2 FOOT
87
90
95
86
100
4 FOOT
90
87
86
95
8 FOOT
87
87.1
86.2
86.5
7 FOOT
87.1
87.3
87.8
87.6
86.8

Figure 6. Temperature survey in a tidally influenced river with marked salinity gradient.

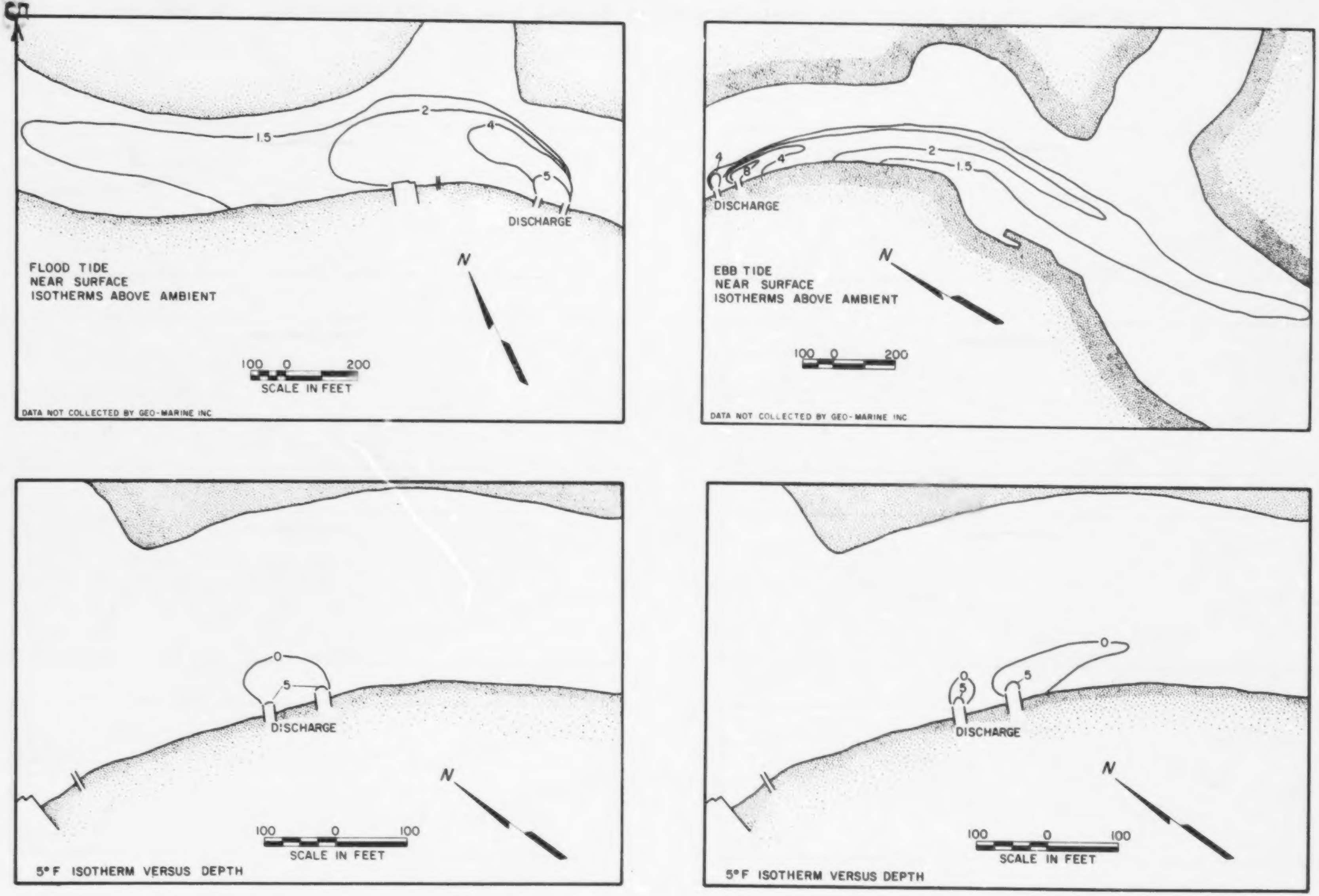
FLOOD TIDE
NEAR SURFACE
ISOTHERMS ABOVE AMBIENT
1.5
2
4
5
DISCHARGE
N
100 0 200
SCALE IN FEET
DATA NOT COLLECTED BY GEO-MARINE INC
EBB TIDE
NEAR SURFACE
ISOTHERMS ABOVE AMBIENT
4
8
4
2
1.5
DISCHARGE
N
100 0 200
DATA NOT COLLECTED BY GEO-MARINE INC
0
5
DISCHARGE
N
100 0 100
SCALE IN FEET
5°F ISOTHERM VERSUS DEPTH
0
5
0
5
DISCHARGE
N
100 0 100
SCALE IN FEET
5°F ISOTHERM VERSUS DEPTH

Figure 7. Temperature surveys of rivers with high tidal amplitudes.

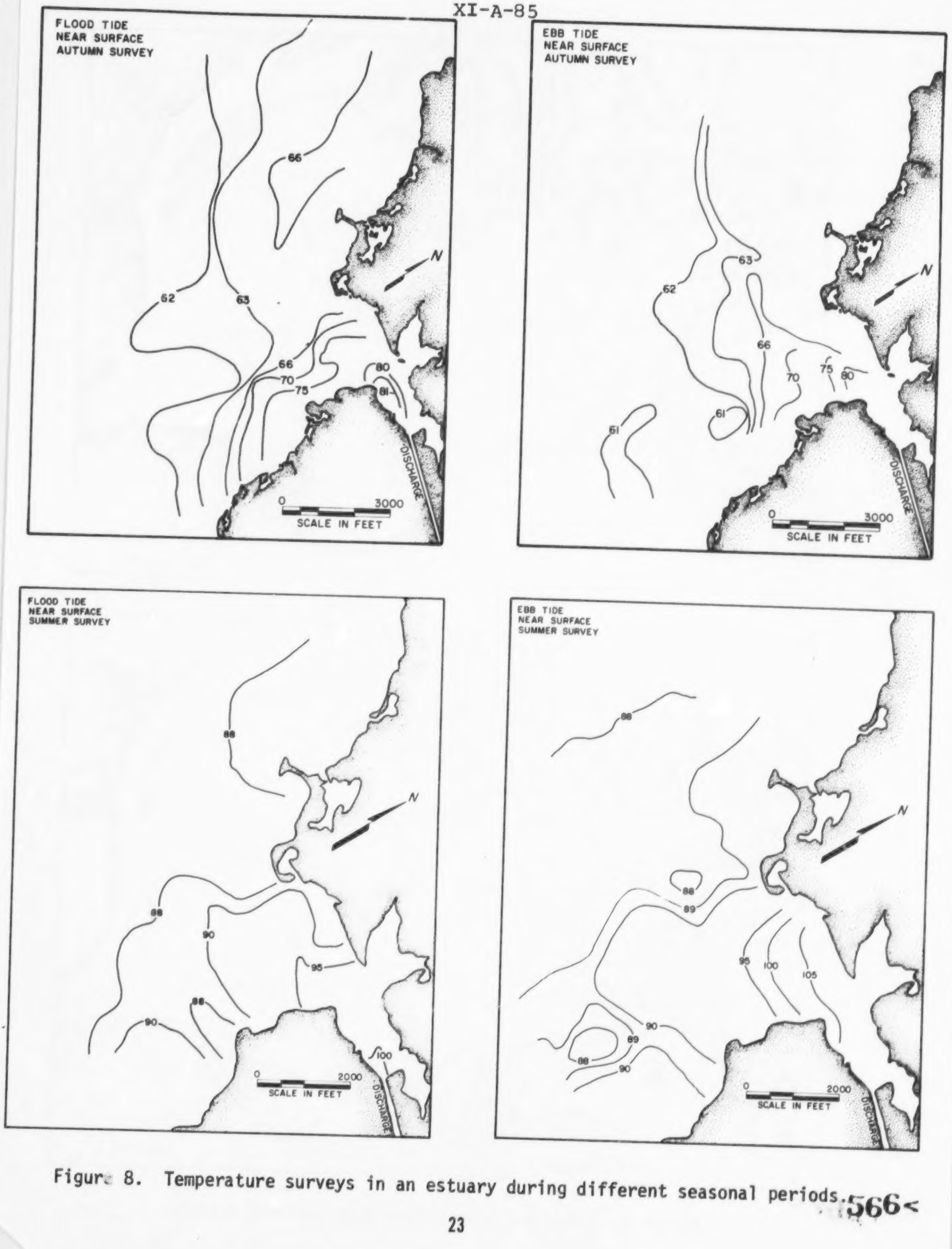
FLOOD TIDE
NEAR SURFACE
AUTUMN SURVEY
66
62
63
66
70
75
80
81
0
3000
SCALE IN FEET
DISCHARGE
N
EBB TIDE
NEAR SURFACE
AUTUMN SURVEY
63
62
66
70
75
80
61
61
0
3000
SCALE IN FEET
DISCHARGE
N
FLOOD TIDE
NEAR SURFACE
SUMMER SURVEY
88
88
90
95
88
90
100
0
2000
SCALE IN FEET
DISCHARGE
N
EBB TIDE
NEAR SURFACE
SUMMER SURVEY
88
88
89
95
100
105
90
89
88
90
0
2000
SCALE IN FEET
DISCHARGE
N

Figure 8. Temperature surveys in an estuary during different seasonal periods.

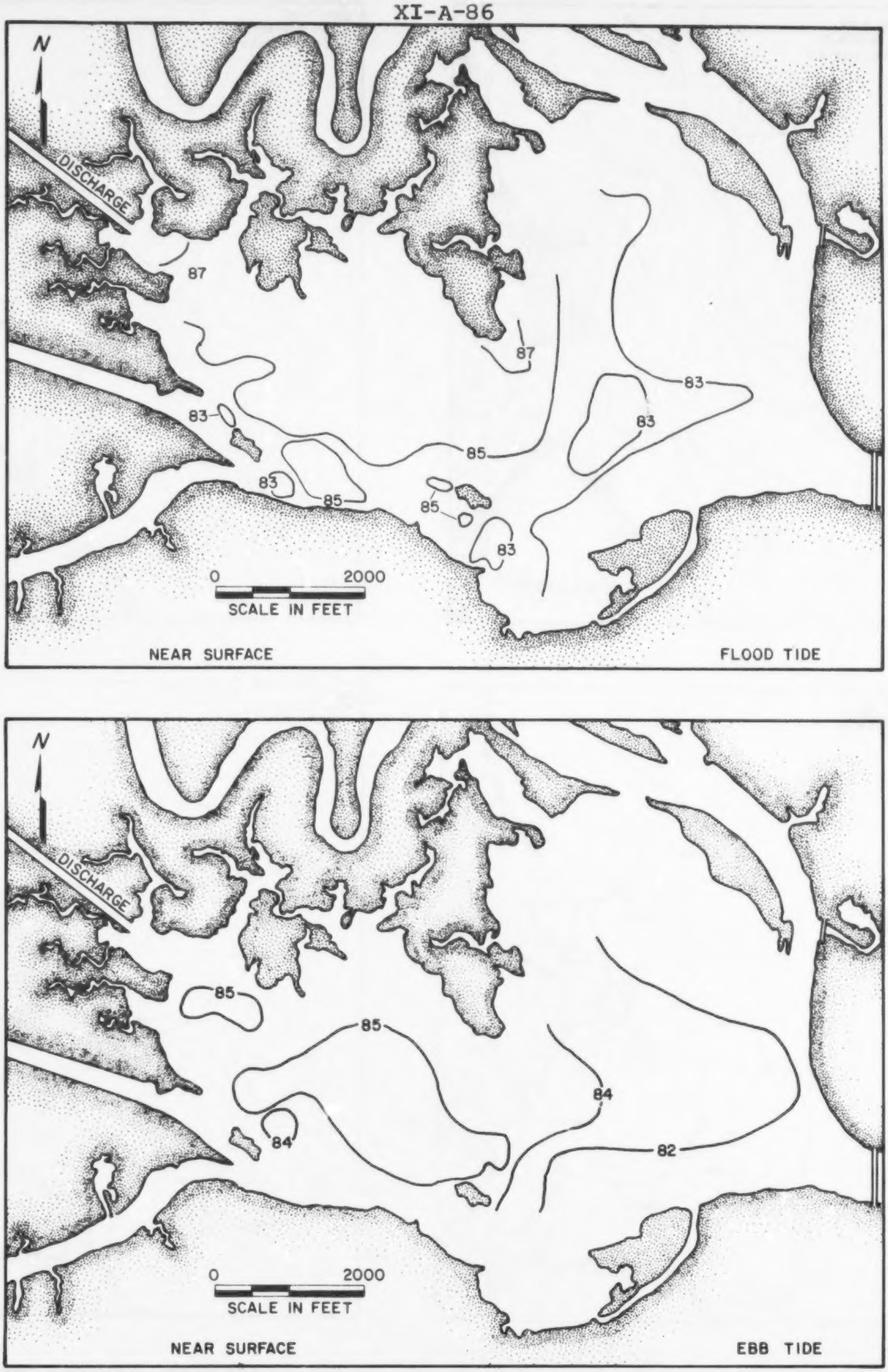
N
DISCHARGE
87
87
83
83
83
85
83
85
85
83
0
2000
SCALE IN FEET
NEAR SURFACE
FLOOD TIDE
N
DISCHARGE
85
85
84
84
82
0
2000
SCALE IN FEET
NEAR SURFACE
EBB TIDE

Figure 9. Temperature profiles in a confined estuary.

XI-A-87

ABSTRACT

OMIT

A Striped Bass Model for Power Plant Evaluation

By

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A striped bass population dynamic model was developed for the San Francisco Bay-Delta. The model was based on the empirical data for 1) percent female of the spawning adults, 2) eggs per female for different age groups, 3) egg mortality, 4) egg grazing by young-of-the-year, 5) monthly migration pattern between the Bay and the Delta, 6) mortality coefficients for different age groups, 7) cannibalism, and 8) fishing mortality. Egg mortality was calculated as a function of net Delta outflow. Entrainment losses of egg larvae and young bass by export, diversion, and industrial cooling systems were also accounted for.

The model divided the bass population into two regional groups, i.e. Delta and Bay-Ocean, allowing for inter-group migration. Observed spatial distribution of egg/larvae and young bass were used to estimate their relative densities for entrainment computations. Simulation can be made for serveral years with a monthly time step.

The model was calibrated with California Fish and Game data for 1959-1974. Evaluations are made for the power plant effects in terms of the entrainment loss of young bass and thermal blocking of migration.

SESSION XI-B
OPEN SESSION II

OMIT

XI-B-113

Prediction of Combustion Characteristics For Refuse Derived Fuel (RDF)

by

Robert J. Schoenberger, Drexel University
Jan K. Sonsteby, Pennsylvania Power and Light Company
Aurel M. Arndt, Lehigh County Authority
Robert M. Gruninger, Malcolm Pirnie Inc.
Jacob Gibs, Drexel University

Abstract

The escalating costs of municipal refuse disposal coupled with continuing pressure on the cost of fossil fuels has resulted in numerous suggestions to use solid waste as a fuel. Methods commonly used to recover the energy include mass (unprocessed) burning in water-walled furnances or boilers, recuperation in waste heat exchangers, and separation of the combustible fraction to enhance the combustion characteristics so that (1) the fuel may be treated or pelletized for storage and subsequent firing (2), the fuel can be burned as a small fraction (5-20%) of the fuel (generally coal) in existing utility boilers or (3) the RDF may be burned in special furnaces to produce a fuel gas or liquid.

Whatever approach is used the burning characteristics of the fuel must be known, particularly the heating value, ash content and chemical characteristics of the ash. Other characteristics of lesser concern include the percent sulfur, nitrogen and chloride. These elements have been implicated in corrosion problem attendent to some existing facilities.

The paper offers comprehensive data on the characteristics of RDF from two locations: Philadelphia and Allentown, Pennsylvania. In excess of 800 separate samples were analyzed to determine the mean value and range for the parameters of ash, volatile matter, silica, iron, chloride, sulfur, organic nitrogen, apparent density and water soluble percentage. The Allentown data include determination of the heating value, volatile matter and ash as a function of percent of fuel separated from the waste stream by an air clarifier.

Data to be presented are particularly useful in design of RDF facilities for use in coal burning boilers. Of prime importance is the adjusted percent of ash and its distribution or fly ash a bottom ash and the volume and weight of refuse which must be fired to achieve a given percentage of RDF in the fired fuel.

XI-B-115

OMIT

MINNESOTA AERIAL INFRARED PROGRAM

The Minnesota Energy Agency (MEA) received an appropriation in the amount of $50,000 from the 1976 session of the Minnesota Legislature for conducting a pilot aerial infra-red thermography project. The project was intended to determine the feasibility of using IR thermography as an aid in conservation measures--particularly to indicate buildings having excessive heat loss through their roofs. Not more than half of the aerial flyovers are to be conducted in the Twin Cities Metropolitan Area.

The program will consist essentially of gathering IR thermographic data from carefully selected sites and distributing the information, with adequate assistance in its interpretation, to local participants who would in turn instruct the public in the specifics of energy conservation in buildings determined to be wasting energy. The U.S. Environmental Protection Agency has agreed to supply technical support for the program, and several utilities and political sub-divisions have expressed strong interest in participation, and even in the possibility of further support.

Other activities of the program would include: a) preparation of a users manual that would aid other states in setting up an aerial thermography project, b) preparation of materials to aid in interpretation of IR imagery, c) analysis of the energy impacts of the program, and d) submission of an interim and a final report that detail the pilot program and make recommendations for replication.

Training and other materials prepared during the program would be included in the final report.

Support for the concept of aerial thermography was considerably boosted by the results of a preliminary pilot thermography project conducted by EPA in the early spring of 1976. At the time of this pilot project--centered mainly over Rochester, Minnesota--EPA performed a flyover of the Minnesota Capitol Complex in St. Paul and the Minneapolis campus of the University of Minnesota. Copies of the University imagery were provided to the University Physical Plant Maintenance and Operations office. That office reports making considerable use of the imagery as a tool for detecting exceptional heat losses from building roofs. The University enthusiastically supports further IR thermography work.

25-45-17

XI-B-117

INTEGRATED STEAM SYSTEMS FOR ELECTRIC POWER GENERATION FROM WASTE HEAT

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ABSTRACT

Packaged steam power systems for electric power generation from incinerator waste heat have recently become available in a price range permitting economic application over a wide range of incinerator sizes. Typically, about 400 kilowatt-hours per ton of waste can be generated from these systems, which are available in the power range from 500 kilowatts to 15, 000 kilowatts. Corresponding incinerator sizes, therefore, range from as low as 30 tons per day throughput to larger systems. The economics and performance of these power systems are presented in this paper for a range of potential applications.

INTRODUCTION

The total generation of post-consumer wastes in the United States is presently about 150 million tons per year[1]. Projections indicate that these wastes will increase to 170 million tons in 1980 and 200 million tons in 1985. The fuel value of the wastes is typically 9 to 11 million Btu per ton. Assuming an average value of 10 million Btu per ton, the present 150 million tons per year represents a potential annual energy source of 1.5×10^{15} Btu (1. 5 quads). This waste-fuel potential is 2 percent of the total overall annual energy use in the country (approximately 75 quads, including all energy forms such as coal, oil, natural gas, nuclear, etc.). In terms of equivalent barrels of oil, the waste fuel potential in 1977 is equal to 250 million barrels of oil. On a daily basis this represents 685, 000 barrels of oil equivalent per day or close to 10 percent of the nation's oil imports.

Post-consumer waste, therefore, should be viewed as a substantial and valuable source of energy. The current requirement for disposing of wastes needs to be realigned in terms of how best to utilize or tap the energy content of the wastes. Numerous industrial and governmental programs are investigating various approaches for economically increasing the use of waste materials. These efforts include material recovery (metals, wood fiber, glass, etc.), conversion to alternate fuel forms, and direct combustion of the wastes with heat recovery in the form of steam. The steam can be used for heating (process applications) or, more probably, for electrical generation. The general trend toward electrical generation results primarily from the difficulties of finding a local steam consumer with nearly constant steam demand. The lack of satisfactory steam consumers tends to favor the generation of electricity which can be distributed over a wide area and to a larger number of customers.

PACKAGED STEAM POWER SYSTEMS

Until recently, the generation of electricity was considered to be limited to large incinerator installations because of high specific costs associated with small steam turbine systems. Packaged steam power systems, however, have become available in a price range permitting economic application over a wide range of incinerator sizes. Typically, about 400 kilowatt-hours per ton of waste can be generated from these systems. The systems are available in the power range from 500 kilowatts to 15,000 kilowatts. Corresponding incinerator sizes, therefore, extend from as low as approximately 30 tons per day of waste throughput to 900 tons per day and larger.

Economic small steam power units are achieved by factory assembly and testing of packaged systems ready for installation. The relative savings realized from factory versus field assembly of power systems is similar to that achieved for packaged steam boilers. The complete power system package includes steam turbo-generator, condenser, feedwater system, lubrication system, and controls. The systems can utilize dry saturated or superheated steam over a wide range of steam pressures. An overall view of such a packaged system is shown in Figure 1. The systems are compact and require a minimum of installation time and space. Typical space requirements are illustrated in Figure 2. The power systems use multistage geared steam turbines to achieve high turbine efficiencies. Typical steam flow conditions versus output power are illustrated in Figures 3 and 4. The systems are available for condensing or backpressure operation and are adaptable to a wide range of plant requirements. Specific power system costs are illustrated in Figure 5 as a function of power level. Above the 1500 kilowatt level, the specific costs are relatively constant at approximately $ 550 per kilowatt. For those plants requiring installation of a waste-heat boiler, the total installed cost of the power system plus waste-heat boiler is approximately $ 700 per kilowatt.

Power System Economics

The economics of the steam power system depends on many factors relating the initial incremental investment to the overall discounted rate of return on that investment. First, consider typical industrial economic conditions. After investing in the installed power system, the industrial user will realize a gross savings in terms of the number of kilowatt-hours of electrical power produced multiplied by the cost of electric power he would have to pay if the power were purchased from the local utility. The cost of purchased power varies from location to location, with the present national average approximately \$ 0. 03 per kilowatt-hour. Electric costs have escalated rapidly in the past few years and will probably continue to rise in the future. Net savings are obtained by reducing the gross savings by the required operation and maintenance costs of the power system. These O&M costs are typically \$ 0. 003 per kilowatt-hour. From these net savings, the industrial user must pay taxes which depend on the tax rate, depreciation schedule, and investment tax credit applicable to him. The after-tax income can then be related to the original investment in terms of discounted rate of return which is a standard technique of evaluating investment opportunities. Figure 6 summarizes the results of this economic analysis for typical industrial conditions. Discounted rates of return are shown in parametric forms as a function of initial investment costs and the cost of purchased power. For example, at a power system investment of \$ 500 per kilowatt and purchased power costs of \$ 0. 03 per kilowatt-hour, a discounted rate of return of about 30 percent is realized under the listed industrial economic conditions.

Now let's consider a specific incinerator application. Assume an incinerator with three-shift operation 5-1/2 days a week handling 120 tons of waste per operating day. The capacity factor is 80 percent. With an average power generation of 400 kilowatt-hours per ton, the power level is 2000 kilowatts. As shown in Figure 5, the incremental installed cost of the packaged steam power system is approximately \$ 550 per kilowatt if steam boiler facilities are already available at the incinerator, and approximately \$ 700 per kilowatt if a waste-heat boiler must be included in the installation. If the incinerator is privately owned, the economic summary presented previously in Figure 6 is generally applicable and discounted rates of return of approximately 29 percent and 25 percent are realized respectively for the power system and power system plus waste-heat boiler cases. For municipal or public owned incinerators, the economic picture is altered substantially by the lack of tax related costs. Under tax-free conditions, the corresponding rate of return is increased to 43 percent and 34 percent. Economic summaries for both privately and publicly owned incinerators are shown in Table 1.

Combined Incinerator-Power System Economics

The incremental costs of the electric power system can be combined with basic incinerator costs to establish typical overall economic data for waste incinerator-electric power energy recovery installations. Recent studies[2] of the effect of waste transportation costs on incinerator economics indicate that incinerators in the order of 100 tons per day tend to be more economic than the large 1000-ton-per-day units considered in the past. These relatively small incinerators presently constitute the majority of incinerator installations in the country and are particularly important to a nationwide energy conservation effort because of the increased siting difficulties and community resistance associated with large centralized systems. The controlled-air type of incinerator appears to be particularly attractive in this size range because of reduced air emissions and compatibility with factory assembly of complete units or modules.

Reference 2 lists installed costs of small controlled-air incinerators in the range from $ 12,000 to $ 14,000 per daily ton of capacity, and operating costs in the range from $ 7 to $ 8 per ton of waste incinerated. In mid 1976 the total capital cost of a 120-ton-per-day design capacity (24-hour operation, 5-1/2 days per week) was $ 1.49 million. This included engineering costs, land acquisition, site preparation, and the incinerator-boiler system. An additional $ 36,700 was needed for mobile equipment used around the plant (the collection and transport of wastes to the incinerator were not included). Combining these costs with the cost of the 2000 kilowatt electric power system described above (2000 kilowatts at $ 550 equals $ 1.1 million) yields a total capital cost of approximately $ 2.6 million for the entire incinerator-electric power system. A summary of the economics of the plant is presented in Table 2. Gross savings or earnings for the installation are generated from two sources. Tipping charges of $ 5 per ton of waste delivered to the incinerator yield $ 175,000 per year and sale of electric power at $ 0.03 per kilowatt-hour yields $ 420,000. With operation and maintenance costs totaling $ 308,000, a net savings of $ 287,000 is realized per year. These net savings translate under typical economic conditions to a 12 percent discounted rate of return for private ownership and 16 percent for public ownership.

SUMMARY

Whether considered as an incremental cost for retrofitting existing steam sources or as part of the total cost of a new installation, packaged steam power systems for electric power generation provide a convenient and

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economic means of energy recovery. Large-scale use of these systems at incinerators and other waste-heat sources will aid in achieving significant reductions in the consumption of purchased energy.

REFERENCES

1. Second Report to Congress, Resource Recovery and Source Reduction, U. S. Environmental Protection Agency, 1974.

2. Hofmann, Ross E., "Controlled-Air Incinerator - Key to Practical Production of Energy From Wastes", Public Works Magazine, September 1976.

TABLE 1

ECONOMIC SUMMARY FOR TYPICAL INCINERATOR POWER SYSTEM APPLICATION

	Steam Power System	Steam Power System Plus Waste Heat Boiler
Installation		
Tons per Day of Waste	120 tons	120 tons
Power Level	2,000 kW	2,000 kW
Initial Investment	$1,100,000	$1,400,000
Gross Savings ($0.03/kWh)	$420,000/year	$420,000/year
Operation and Maintenance	$42,000/year	$42,000/year
Net Savings	$378,000/year	$378,000/year
Net Savings per Ton of Waste	$10.8/ton	$10.8/ton
Discounted Rate of Return		
Private Ownership	29%	25%
Public Ownership	43%	34%

TABLE 2

COMBINED INCINERATOR PLUS ELECTRIC POWER SYSTEM ECONOMIC SUMMARY

Incinerator Costs	
Total Incinerator Plus Boiler Installation	$1,490,000
Mobile Equipment	$37,000
	$1,527,000
Electric Power System Costs	$1,100,000
Total Incinerator Plus Electric Power System Costs	$2,627,000
Gross Savings	
Waste Tipping Fees (35,000 tons at $5)	$175,000
Electric Power (14 x 10^6 kWh at $0.03)	$420,000
	$595,000
Operation and Maintenance	
Incinerator	$266,000
Electric Power System	$42,000
	$308,000
Net Savings	$287,000
Discounted Rate of Return	
Private Ownership	12%
Public Ownership	16%

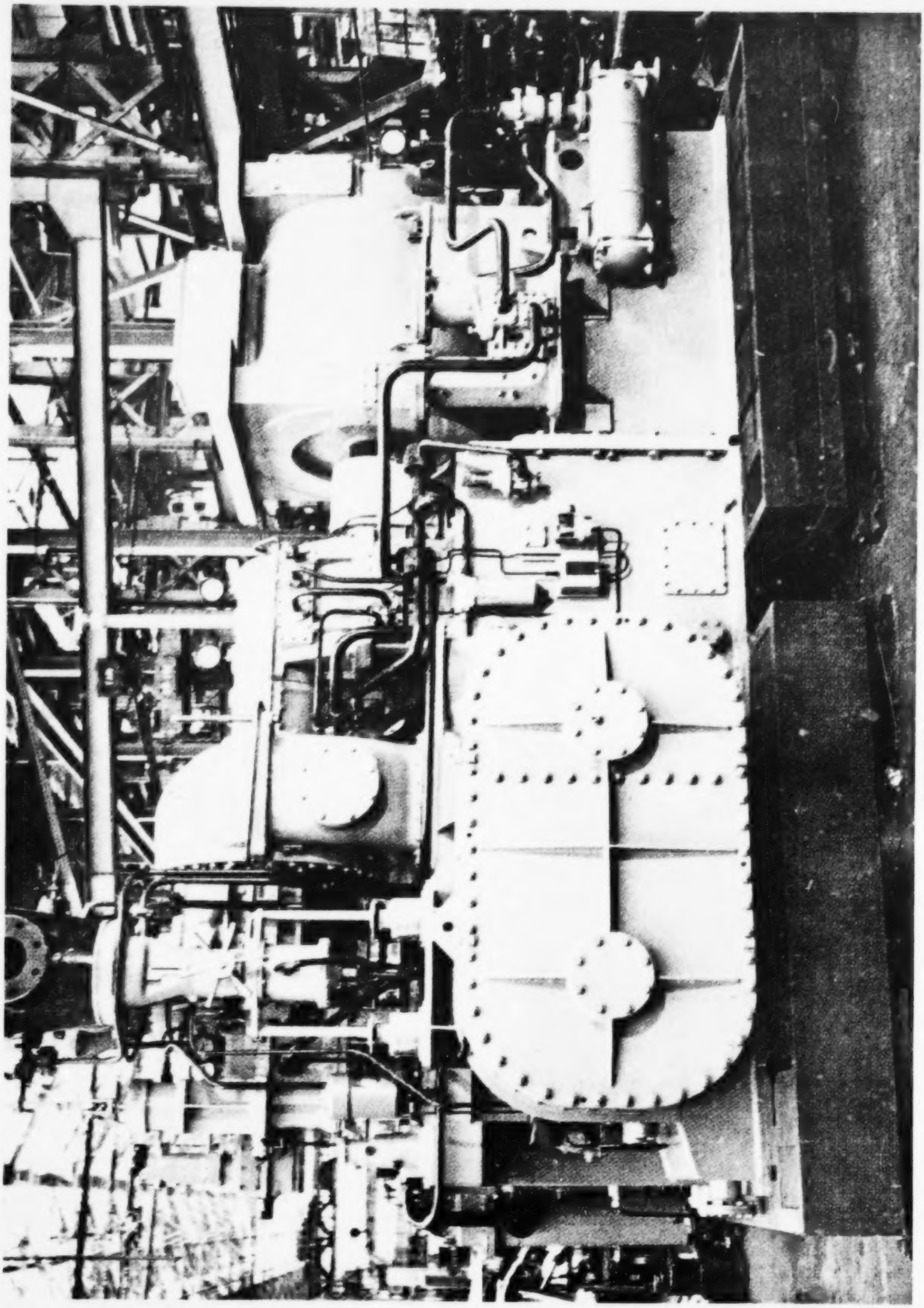
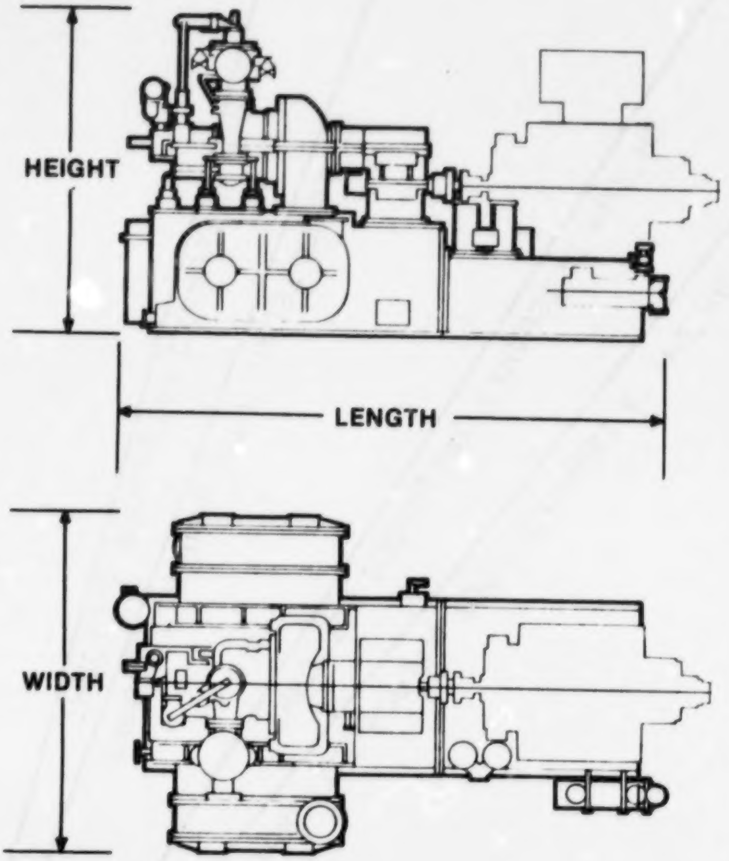


Figure 1. Packaged Steam Power System


HEIGHT
LENGTH
WIDTH

POWER KW	1000	2500	4000
LENGTH FT	20.8	21.5	27.0
WIDTH FT	11.0	11.0	11.8
HEIGHT FT	10.5	10.5	13.3
WEIGHT TONS	7.5	15.0	20.0

Figure 2. Typical Power System Installation Requirements

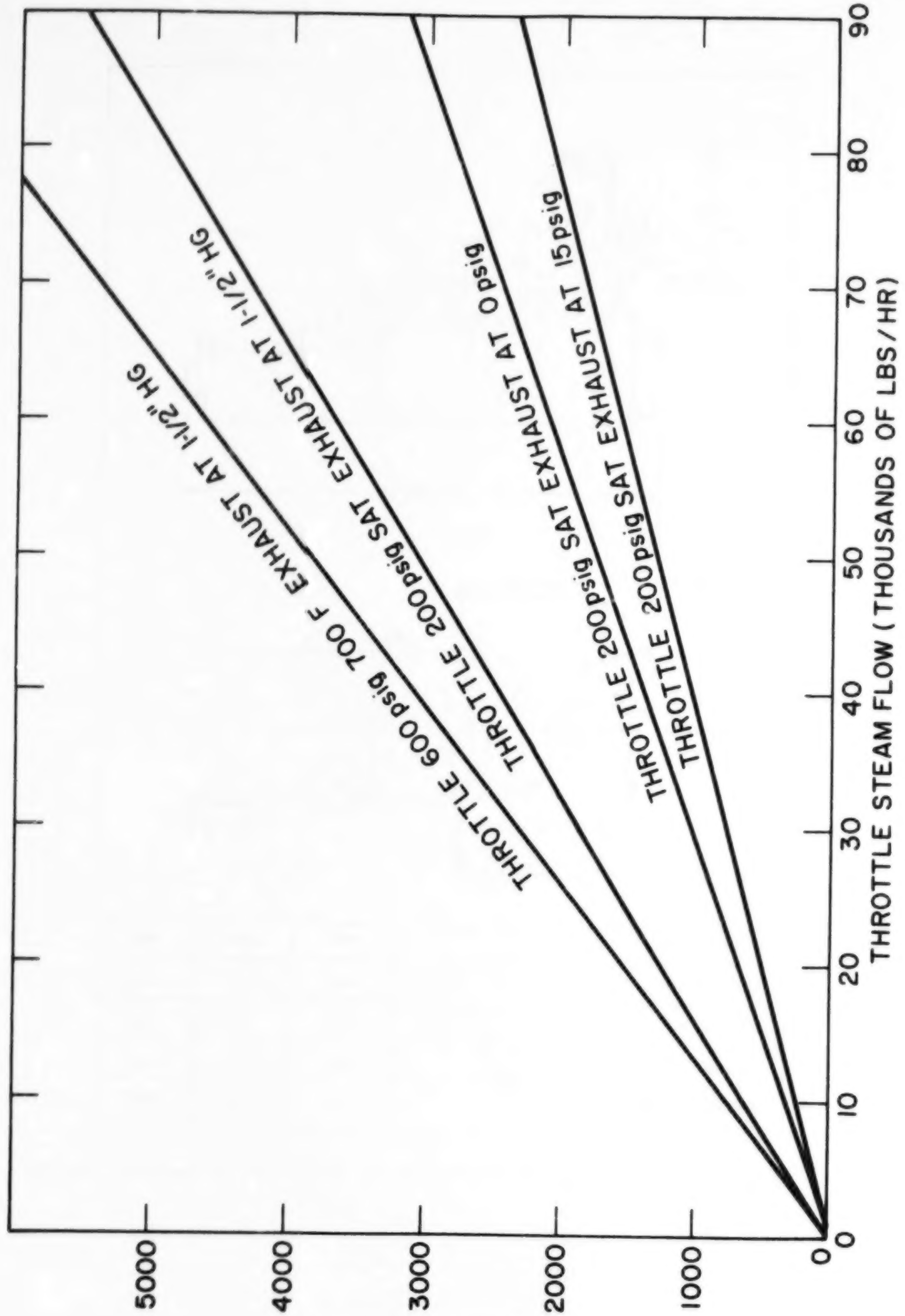


Figure 3. Power System Performance

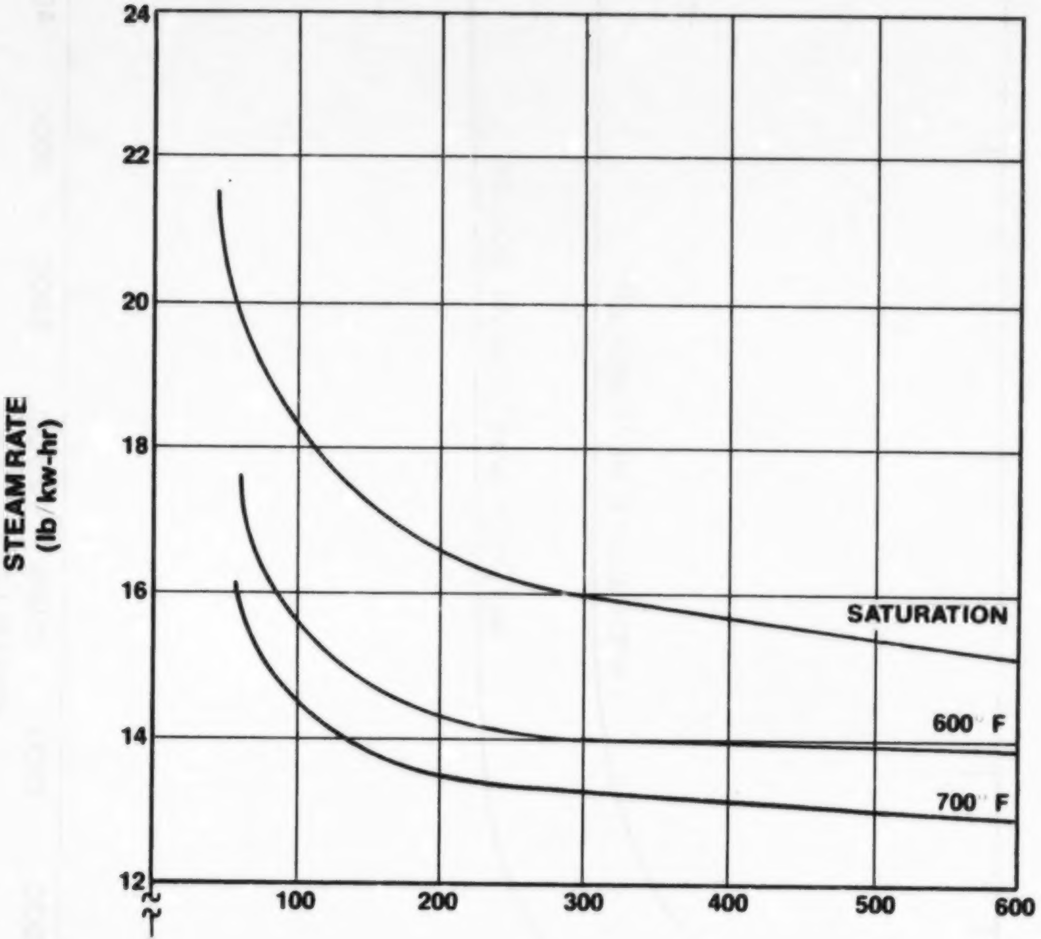


Figure 4. Performance Data for Nominal 1500 kwe Thermo Electron Steam Power System ($T_{Condenser} = 115° F$)

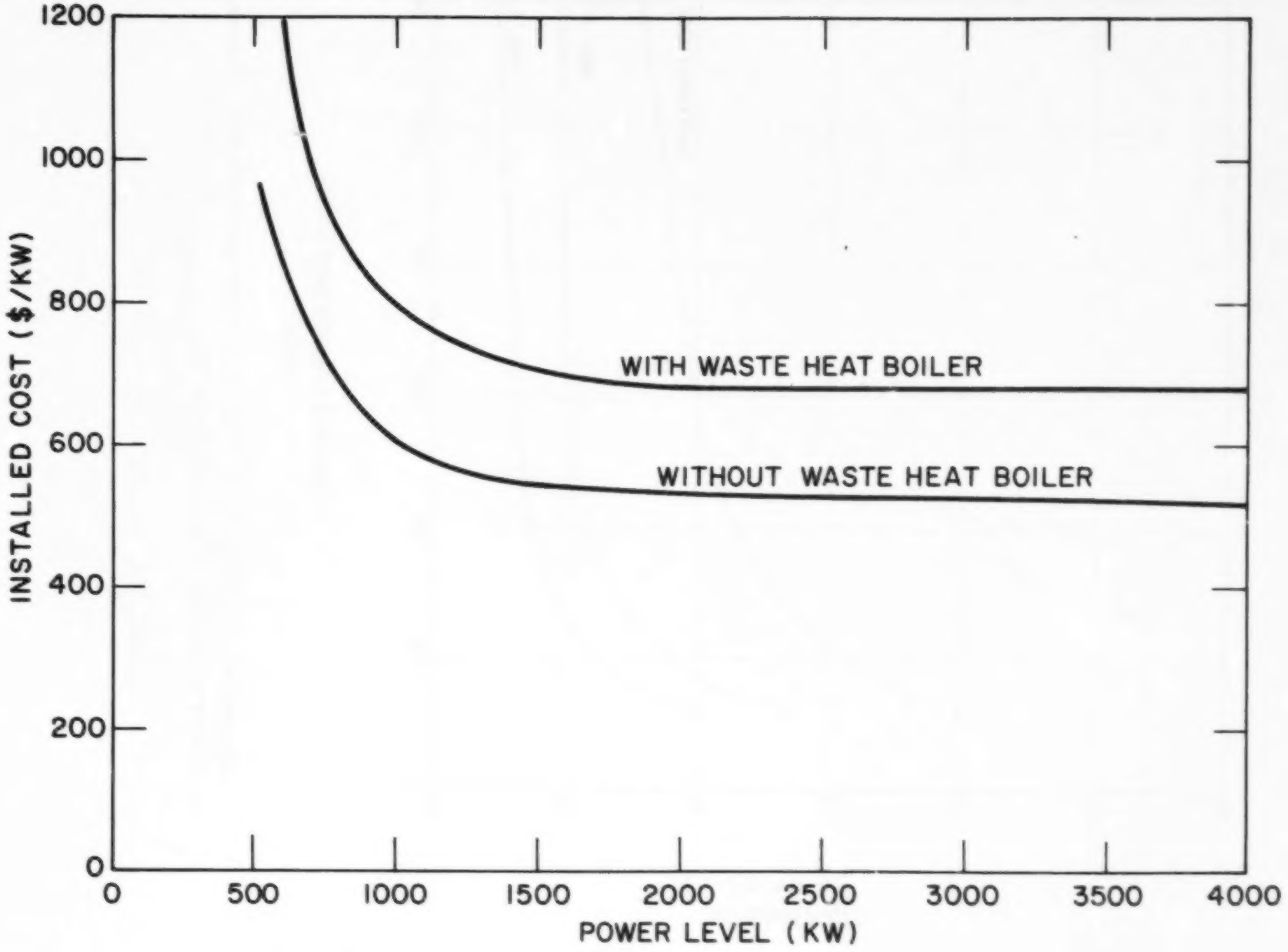


Figure 5. Installed Power System Costs

- ■ 50% TAX RATE
- ■ 20 YEAR PLANT LIFE & ACCELERATED DEPRECIATION(SOD)
- ■ 10% INVESTMENT TAX CREDIT
- ■ 80% CAPACITY FACTOR
- ■ 0.3 ¢/kw-hr CURRENT OPERATION/MAINTENANCE COST
- ■ ANNUAL NET SAVINGS ESCALATION RATE 6%/YR.

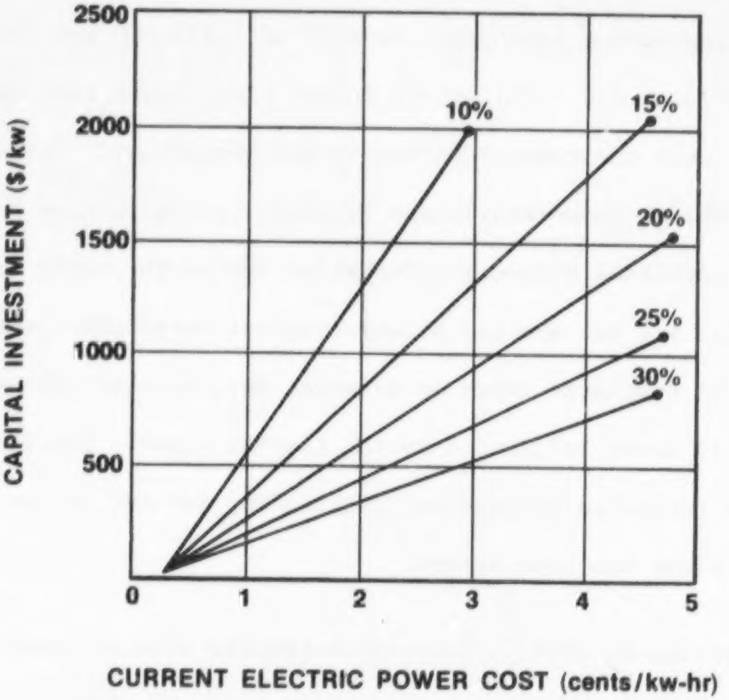


Figure 6. Capital Investment versus Current Electric Power Cost for Various After-Tax Discounted Rates of Return

EFFECTS ON ECOSYSTEMS

The Effects of Thermal Effluents on the Populations of Shipworms (TEREDINIDAE:MOLLUSCA) in the Vicinity of a Nuclear Power Station

The Oyster Creek Nuclear Generating Station, with a licensed power level of 1930 MWt has been generating power since December 1969. The once-through cooling system discharges as much as 1,252,000 gpm (2780 cfs) of heated effluent ($\Delta T \approx 6°C$) into a former tidal creek that empties into Barnegat Bay near the town of Forked River, New Jersey. Increased salinity and higher ambient temperatures due to plant operation have been implicated in a severe localized shipworm infestation during the early 1970's. Two native species and two species of sub-tropical teredinids, not previously known from the discharge creek or Barnegat Bay, have established breeding populations in areas influenced by the thermal plume. Destruction by shipworms of untreated pilings and bulkheading located in the vicinity of the thermal plume has been severe.

During the spring of 1976, cold weather coupled with an extended plant outage and the completion of a wood removal program in the plume area has resulted in a significant reduction in shipworm abundance.

The relative rates of destruction of untreated wood, abundance and distribution of the various species in areas influenced by the thermal plume and in control areas have been studied by numerous investigators. The results of these studies are presented. Environmental parameters limiting the distribution and abundance of the various species present in the vicinity of the nuclear generating station are discussed. Possible mitigative actions that could result in a lessening of attack are described.

XI-B-133

A COMPARISON OF THE BIOLOGICAL EFFECTS OF HEATED EFFLUENTS FROM TWO FOSSIL FUEL PLANTS: BISCAYNE BAY, FLORIDA, IN THE SUBTROPICS; GUAYANILLA BAY, PUERTO RICO, IN THE TROPICS

by

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and

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26-45-20

XI-B-134

A Comparison of the Biological Effects of Heated Effluents From Two Fossil Fuel Plants: Biscayne Bay, Florida, in the Subtropics; Guayanilla Bay, Puerto Rico, in the Tropics

By Anitra Thorhaug and Peter B. Schroeder, Department of Microbiology, School of Medicine, University of Miami, Miami, Florida 33149.

ABSTRACT

A five year study was made at Turkey Point on Biscayne Bay, Florida on the southern edge of the subtropics, where a 32,000 KWe fossil fuel plant was releasing 255 cubic meter sec^{-1} through a one mile canal. The first release of heated effluents was direct with no dilution. Persistent isotherms were established of +5°C, +4°C, +3°C, +2°C, +1°C in a shallow area (1m) dominated by seagrass meadow. In the +5°C, the naturally-occurring dominant seagrasses disappeared; in the +3°C in the summer, the vegetation died, whereupon animals entered the area, consumed the detritus, then departed leaving it denuded. When a dilution regime was instituted, the area formerly +5°C did not recover, but the +1°C and +0.5°C covered large areas, which appeared more productive in terms of plant material than control areas. Areas previously +3°C and +2°C, which now had lowered temperature regimes, appeared to change positively in terms of production of seagrass material and abundance of species of macroalgae. The effluent was then diverted to a second cooling canal, where isotherms of +3°C, +2°C surface water and +2°C, and +1°C bottom water went into fairly deep (3m) estuary, Card Sound, in an area previously altered by a canal. Except for an area of several acres, immediately at the mouth of this canal, effects of the effluent could not be distinguished from statistical variability.

A two year study of the effects of thermal effluents on Thalassia testudinum was made at Guayanilla Bay, Puerto Rico, where a 710 MWe fossil fuel power complex was located. This plant discharged 135,000 cubic meters sec^{-1} water approximately 10°C above the intake water, which ranged from 26°C to 31°C. The discharge water emptied into a semi-enclosed cove in which some mixing occurred. A thermal plume flowed from this cove into Guayanilla Bay where beds of the seagrass Thalassia testudinum flats were located. Biomass of Thalassia in beds located in the heated effluent was inversely correlated (P greater than .95) with temperature, but other factors such as turbidity and flow-rate may have contributed to the differences. Chemical pollution from an oil refinery and several chemical plants also occurred. Therefore, a floating transplant box experiment was carried out to minimize factors other than temperature. Plants were transplanted from a Thalassia bed into floating transplant boxes located at various places in the heated discharge. Samples were examined weekly. No symptoms of stress were observed in transplant samples subject to mean temperatures lower than 34.5°C (maximum observed temperatures). Mortality was first observed in samples subjected for 2 weeks to a mean temperature of 35.8°C and a measured maximum of 36.6°C. Death after several weeks of exposure was observed in a sample subjected to a mean of 35°C and a maximum of 36.4°C. Therefore, in Guayanilla Bay, the thermal limit as defined in this study was approximately

36.5°C (maximum temperature) and samples appeared stressed at 35°C and above.

The comparison between the two methods used and the two locations will be made.

The most important principle for waste heat management is that tropical and subtropical nearshore ecosystems are close to the brink of disaster (Thorhaug, 1976) and that extreme caution must be applied as to releasing heat more than 2°C above ambient on nearshore grassbeds.

These studies were supported by ERDA Grant # E(40-1) 4493 and Florida Power and Light Company

I. INTRODUCTION

Although an increasing number of power plants are releasing heated effluents in the subtropics and tropics, and specifically on seagrass-dominated communities, we have little information on the upper temperature tolerances of these seagrass communities as we progress from the subtropics to the tropics. The Caribbean and Gulf of Mexico nearshore and estuarine areas are usually dominated by Thalassia testudinum, turtle grass. It is important to begin to define safe limits of release of heated effluents on various subtropical and tropical communities so that managers and regulators of energy-related industry can have clear guidelines. Minimal environmental damage with maximal energy efficiency is our goal in integrating studies of environmental effects of power plants.

We have selected two estuaries, one tropical and one subtropical, in fairly protected, low-energy environments, both containing Thalassia communities with which to begin such a comparison. One major difference between the two sites is that the Biscayne Bay site was relatively unmodified by man's activities prior to the release of heat, where as Guayanilla Bay had multiple activities prior to and during the heated effluent release.

A. Study Area: Biscayne Bay, Florida

Biscayne Bay is approximately 35 miles long with a maximum width of eight miles. The general shape of the bay resembles the letter "A", and is enclosed to the east by a series of barrier islands which extend north and south. Mean water depth is approximately 7 feet with maximum depth of 12 feet in the south central portion of the bay.

Turkey Point is a narrow spit of land projecting from the western shoreline approximately 3 miles north of Cutter Bank. Water depth in the sampling area averages approximately 4 feet with a maximum depth of 6 feet at the eastern-most station.

Tidal exchange into south Biscayne Bay occurs via the small inlets between the barrier islands that form the eastern boundary, and is quite weak. This is demonstrated by the seasonal salinity contrasts between the bays and the ocean that develops in response to the predominant wet-dry seasons of southeast Florida (Lee & Rooth, 1972).

Mean tidal range is approximately 1.5 feet for the Turkey Point area. The Bay is underlain by a shallow Pleistocene bedrock 2 to 6 meters in depth. Sedimentation includes paralic peat and fresh water calcitic mud swamp deposits along the shorelines. Open bay areas have depths 3 to 3.5 m below sea level with a winnowed quartz and carbonate sand (less than 15 cm) over the bedrock (Wanless, 1967, 1976).

Previous studies of *Thalassia* in these areas include some qualitative distribution studies by Voss and Voss (1955), and Phillips (1960), studies of *Thalassia* and epiphytes by Humm (1964), the effect of hurricane Donna on Biscayne Bay Thomas *et al*., (1961) and detailed morphological studies by Tomlinson & Vargo (1966) and Tomlinson (1969 a & b).

Bay water temperature measured on Pelican Bank, a shallow grass flat beyond the influence of the effluent, varied from a minimum of 10°C in winter to 32°C in summer. The fossil fuel plants increased the water temperature 6-7°C, and the discharge was, on average 5°C above normal. About 10-12 ha were subjected to a temperature elevation of 4-5°C, 60 ha to 3-4°C, 120 ha to 2-3°C, 250 ha to 1-2°C water and over 400 ha to 0.5-1°C (Figures 1 and 3).

In addition to the heat carried by the effluent, there was increased turbidity due to an organic substance, and increased iron concentrations in the effluent. An additional pollutant was copper, probably arising from the use of shark repellents during Air Force rescue training operations. Copper was distributed unevenly in the bay near Turkey Point. The concentrations of nutrient chemicals seemed to be greater than usual for subtropical estuaries. Dissolved oxygen concentrations were usually saturated and the lowest values observed in early morning hours were between 3 and 4 ppm.

B. Study Area: Guayanilla Bay, Puerto Rico

Guayanilla Bay, located on the southwest coast of Puerto Rico, forms a natural harbor that has been selected as a site for industry (Figure 4). In the past twenty years, an oil refinery, several related chemical plants, and a fossil fuel power station have been built there. As a result, the shoreline has been altered, and the waters changed by various effluents.

The oil refinery, owned by Commonwealth Oil Refinery Company (CORCO), is located on the eastern part of the bay and also borders neighboring Tallaboa Bay to the east. Other industries include an olefin factory and the Pittsburg Plate Glass (PPG) monomer factory for polyvinyl chlorine plastic on adjacent sites. At present Formosa Plastic is building a PVC plastic industry there.

To provide power for these industries and for the towns of southwest Puerto Rico, fossil fuel power plants have been built on the bay by the Puerto Rico Water Resources Authority. Two small plants (total 310 MWe) have been in operation for a number of years. In March, 1972, a 400 MWe plant was added. Another 400 MWe plant was added in the summer of 1973. In the past few years the flow of heated effluent into the bay has more than tripled. At the time of the field study, the bay was receiving cooling water from the condensers of the power station at the rate of 1510 m^3/minute.

In addition to heated water, Guayanilla Bay receives chemical pollutants from the oil refinery and various chemical plants. Oil slicks are frequently observed. Moreover, the levels of mercury, cadmium, chromium nickel, lead and vanadium are high in the sediment and chromates and chlorine are used periodically as anticorrodant and antifouling agents in the condensers of the power plant (Kolehmainen *et al.*, 1974).

The heated water, which is approximately 10°C above ambient, is released through a one hundred meter long canal into a semi-enclosed cover of approximately 22.4 hectares. Located in the northeastern corner of Guayanilla Bay, this cove has many of the characteristics of a discharge canal. It is 900 meters long and about 200 meters wide. Its mouth, where it opens into Guayanilla Bay, is approximately 30 meters across. On the south side of the cove is a natural mangrove shoreline. The other side has been built up with fill material. The cove holds no significant benthic vegetation. The bottom has been scoured by the water flow and contains few or no macrophytes. Long strands of filamentous blue-green algae were seen attached to floating boxes moored in the cove and may have been the major photosynthesizers in the cove. The temperatures in the cove generally range from 35°C to 40°C depending on distance from the discharge canal and season. Ambient water temperature in Guayanilla Bay varies seasonally between 27°C and 31°C.

Outside the mouth of the cove an area of the bay approximately 50 hectares in extent is also subjected to higher than ambient temperatures. This area is partially bordered by mangroves. Two bottom communities are important here. These are the turtle grass community, dominated by *Thalassia*, found on shoals at depths up to approximately one meter, and the *Halophila-Acanthophora-Caulerpa* community, on soft sediments in deeper places. A thermal gradient exists in the water between the mouth of the heated cove and the small mangrove island, Cayo Mata, some 600 meters northwest.

Five sampling stations were established in various turtle grass flats in western Guayanilla Bay (Schroeder, 1975). Station 1 was located to the south and some 150 meters out from the entrance of the thermally affected cove; Station 2 was located 300 meters west of the cove's entrance, and Station 3 was located near the small mangrove island, Cayo Mata, about 600 meters to the west southwest of the entrance. Stations 4 and 5 were control stations located north of the filled spit, in that part of the bay from which the cooling water was drawn (Figure 5).

II. METHODS

A. Turkey Point

1. Field procedure for Thalassia

Thalassia blades were counted in 0.04 m^2 at eight stations in the Turkey Point area. An additional 0.01 m^2 was used to define an area at each station where the Thalassia blades were marked for growth and production studies. In Card Sound, a 0.04 m^2 frame was also used for counting at stations were Thalassia blades were abundant (2000 blades/m^2 or more). Where blades were sparse (fewer than 2000 blades/m^2), a 0.25 m^2 was used. Comparative counts between 0.04 and 0.25 m^2 were made to permit statistical evaluations. Measurements were made every 2 weeks from April 1970 to December 1973.

The field sampling procedure for Turkey Point and Card Sound was as follows:

a. Grass blades were counted during the first and third weeks of each month.

b. The 0.01-m marking square was placed near the permanently fixed counting square, and the individual Thalassia blades were marked with plastic-coated staples (Zieman, 1970) in the first week of the month. The staples were placed at the point where the grass blades emerged from the stipes.

c. Two weeks later all blades within the marking square were broken off at the point where they emerged from the stipes and were collected.

d. Each counting square was photographed during the third week of every month using a uniform camera angle to allow the construction of a time series.

e. Water turbidity, wind, current, and other factors were recorded.

f. Plants were examined for flowers, fruit, buds, and newly emerged shoots.

2. Laboratory procedure for Thalassia

The Thalassia collected in the field was measured by the following procedure, which is similar to that of Zieman (1970):

a. Blade width was measured.

b. The length from the bottom of the blade to the bottom of the implanted staple was measured.

c. Blades were washed and shaken for 2 to 5 min in 50% reagent-grade phosphoric acid to remove attached organisms, predominantly foraminifera micromollusks. The blades were then washed with tap water.

d. New growth (below the staples) was separated from the rest of the blade.

e. The new blades and the new growth of mature blades were dried for 3 days at 110°C, cooled in a desiccator, and weighed.

B. Guayanilla Bay

1. Thalassia standing crop determination

Measurements of the standing crop of Thalassia in the five Guayanilla Bay Stations were made during the summer of 1972. Samples were taken from the turtle grass beds with a specially designed corer which removed a uniform round plug 1/50 square meter in area and twelve to sixteen centimeters deep. The device was designed to collect a sample of the Thalassia plants with substrate and associated organisms. Plant samples were separated from the substrate and the associated organisms by washing. The turtle grass plants were divided into five fractions: leaves (green and dead), roots, rhizomes, shore (vertical) shoots, and sheaths. The plant parts were dried at 110°C and weighed. The biomass data from the five Thalassia bed stations were analyzed for significant differences by F-test.

2. Thalassia transplant experiments

Turtle grass beds in Guayanilla Bay subjected to different temperatures had differing substrates. The plants in those beds nearest the mouth of the heated cove were growing in coarse, calcareous gravel composed of fragments of coral and mollusc shell. The substrate in the control area was much finer and composed primarily of calcareous mud. A field experiment was designed in which temperature varied but substrate did not.

Floating wooden plant boxes approximately 45 cm square were constructed. The boxes were designed to hold nine identical Thalassia core samples taken with the Thalassia sampler described previously. The Thalassia cores were held in short plastic bags that contained the substrate but did not interfere with the leaves. The transplant boxes were fixed to concrete block anchors by polypropylene 6mm (¼ inch) rope 7.5 meters in length and floated with styrofoam, so that the tops of the leaves of the plants were maintained approximately 35 cm below the water surface. Ten transplant boxes were placed in Guayanilla Bay at locations where water temperatures varied from the ambient temperature in the bay to the highest temperature that could be obtained in the heated effluent. (Location of the transplant boxes are shown in Figure 5).

One sample was removed and replaced in each box weekly so that at the end of ten weeks each box contained samples subjected to water temperatures characteristic of that site from one to nine weeks. Periodically, all samples in each box were collected and a new cycle started.

When each sample was collected the water temperature at the box was recorded. Temperatures of the power plant outfall and the water temperatures at the five Thalassia bed stations were also taken weekly for reference. A calibrated mercury thermometer was used for measurements and continuous recording of thermal fluctuations was obtained at select sites using Peabody-Ryan thermographs. In addition, Taylor maximum-minimum thermometers were used. Thalassia transplants were subjected to temperatures ranging from below the measured mean in the control area to ones well above the thermal limits of the plant. The salinity of the water in the vicinity of the transplant boxes was checked periodically by hydrometer or refractometer and, in all cases, found to approximate the salinity of seawater (35 part per thousand).

Notes were made on the condition of all the transplants in the transplant boxes at the time samples were collected. The presence of many necrotic spots on leaves, chlorosis (either browning or clearing), heavy encrustation by barnacles, or flaccidity of leaves was considered to be a sign of stress. Complete loss of green color was a reliable indication of plant death. Stress and death data were evaluated for correlation with temperature and length of time the samples were at the site.

III. RESULTS

A. Biscayne Bay, Florida

In the area near the mouth of the effluent canal where the mean temperature was elevated 5°C above ambient, blue-green algae became the dominant species in place of the Thalassia, which completely disappeared. Destruction of the previously abundant Thalassia was complete, even to the roots and rhizomes which were dead by the end of the first summer of elevated temperature. Simultaneous animal studies showed a sharp decline in both numbers of individuals and diversity of species (Roessler, 1971). The original food web virtually disappeared, including the important commercial species.

The area of 4°C elevation produces a strong degradation in the Thalassia beds that were able to survive at those temperatures (Figure 2). Even though in some isolated cases abundance increased, there was a considerable drop in standing crop due to a more than 50% decrease in blade width and length. Growth was slowed and productivity of Thalassia was reduced. Developments of dense blue-green algal mats (species not identified) were observed to cover most of the Thalassia beds when water temperatures exceeded 33.5°C for more than two or three days. Also, due to higher than normal winter temperatures in this area, seasonal fluctuations in standing crop were less than the unstressed areas, with peaks occurring in early spring and late fall (Table 1).

The area of 3°C over ambient was not as sharply defined as the plus 4°C area. There was a reduction in standing crop, productivity and growth, but not to the extent of the plus 4°C area. Due to frequently flacid, mottled, and dark coloration of the grass blades (as opposed to the normal bright green) during peak summer temperatures, as well as the reduction in numbers and diversity of animals, it is safe to conclude that the beds in this area were generally unhealthy.

The area of 2°C temperature elevation did not decline in appearance to the extent that was evident in the 4°C and 3°C areas. Although blade size was nearly equal to that of the unstressed areas, growth was slowed and productivity averaged less as compared to unstressed stations in the same area.

The plus 1°C elevated area was considered the least of thermal stress. For the most part, the *Thalassia* was healthy in appearance and approximately normal in size and abundance. Productivity was considered normal for the Turkey Point area. Animals were also observed to be abundant and diverse.

Other general characteristics of the thermally stressed areas were a gradual decrease in sexual reproductive structures (i.e. flowers, fruits, buds) and a marked increase in asexual structures (short shoots). As compared to Card Sound, field observations at Turkey Point detected far fewer flowers (1/3), buds (1/6), and no fruits, but three times as many new short shoots.

Highest water temperatures observed during 1971 at any time in the Turkey Point area were 37°C - 38°C during June 21 and 22, 1970, and July 12-20, 1970. The maximum recorded temperature was 38.5°C on July 15, 1970. Normal maximum bay ambient for that time of year is approximately 30.5°C ± 1°C.

Diving observations showed that *Thalassia* was covered by an estimated 10 cm layer of sediment in an area of about 2-3 ha within the confines of a sediment containment boom used in the dredging of the canal opening into Card Sound. As a result a leaf kill occurred. The rhizome system was not destroyed by the siltation, so that when the silt was removed by currents from the canal the plants were re-exposed and regrowth of blades occurred.

Results show that Thalassia growth in the major portion of Card Sound was not significantly affected by the discharge. Growth in mg/blade/day (Table 2) was significantly greater ($P=0.025$) at stations 0204, 0404, 0504, 0604 and 1103 during the year following the closing of the discharge canal than during the 13 month discharge period. However, mean growth at stations 0204, 0304, 0404, 0504, 0603 and 0604 was also significantly greater ($P=0.025$) during the year after the canal closed than it was during the year prior to the opening. In addition, although some differences in production values (Table 2) were found between stations affected by the plume compared to control station, these differences were not significant at the 0.025 level. Table 2 shows standing crop (in terms of abundance of blade) and production in a series of stations in Card Sound. Stations 0403, 0503, and 0703 were controls for Station 0603, which was affected by effluents +2°C above ambient in 1972. Similarily, 0504 and 0704 were controls for 0604, which was subjected to effluents +1°C above ambient in 1972. No significant differences in mean growth were observed in the year before the canal opened as compared to the mean growth during the discharge period for the total sixteen stations. Since Card Sound is highly variable with respect to internal changes in salinity, temperature and turbidity, large variability in production was expected and found among years from 0.6 to 1.0 of g dry wt/m^2/day for mean of 16 stations and among stations from 5.6 to 0.3 g dry wt/m^2/day.

B. Guayanilla Bay, Puerto Rico

1. Standing Crop

Maximum measured temperatures and average differences in temperature between three Thalassia stations (1, 2, and 3) near the outlet of the thermal cove and the two control area stations (4 and 5) are shown in Table 3. Each station was visited weekly and the water temperature measured during the middle of the day when water temperature was at its diurnal maximum. The control temperature was taken as the means of the temperatures at Stations 4 and 5. Continuous recordings from thermographs placed in the beds during part of the period of study indicated that maximum measured temperatures (recorded periodically) were not exceeded by actual temperatures. The higher temperatures at Stations 1, 2, and 3 were caused by the thermal discharge from the mouth of the heated cove.

Maximum recorded temperatures at Stations 1, 2, and 3 were 35.0°C, 33.0°C, and 34.0°C respectively. Maximum recorded temperatures at Stations 4 and 5 were 31.1°C.

Mean temperatures at Stations 1, 2, and 3 differed from mean temperatures at the controls by +4.3°C, +3.3°C, and +2.7°C.

The standing crop values and biomass of *Thalassia* plant parts from Stations 1 through 5 are shown in Table 4. The standing crop (grams dry weight of *Thalassia* per meter square) and plant-part biomass (grams dry weight of plant parts per meter square) were inversely correlated with increase in mean temperature. Dry weights of root material and green leaves showed the greatest inverse correlation with temperature. Dry weight of vertical shoots showed the least correlation. Biomass data were subjected to analysis of variance. In no case was a significant difference ($P < 0.05$) found between the control stations (Stations 4 and 5). However, significant differences were found in biomass of plant parts between each of the heated stations and between each of the heated stations and the unheated control stations. Mean temperature in Thalassia bed Station 3 differed from the mean ambient temperature in the control area by only 2.7°C, and showed significant differences from the control stations only in dry weight of root material. The standing crop in Station 3 did not differ significantly from that of the controls. Significant differences were found between the standing crop of Stations 1 and 2 and the other stations.

2. Transplant Experiments

Guayanilla Bay was visited weekly during the study period. Minimum and maximum recorded temperatures of the water surrounding the Thalassia transplant boxes are shown in Table 3. Field observations were made on the apparent health, stress, or death of all plant samples in the transplant boxes. The criteria used in these observations were described in the methods section.

The floating transplant box experiment was designed to minimize variation in substrate and illumination so that the effect of temperature alone could be examined. All plants were collected from the same Thalassia bed (same substrate) and were maintained at approximately the same depth.

No signs of stress were observed in transplanted Thalassia subjected to mean temperatures lower than 34.5°C or maximum observed temperatures lower than 35.0°C. At temperatures above 35.0°C the samples showed all the symptoms of stress previously described.

Stress, as described previously, was first observed after two weeks in a sample subjected to a maximum temperature of 35.0°C and a mean temperature of 34.5°C.

Complete loss of green color in leaves was found to be a visual indication of death in Thalassia. Mortality was first observed in two weeks in a sample subjected to a mean daytime temperature of 35.8°C and a maximum temperature of 36.6°C. Mortality was observed after seven weeks in a sample subjected to a mean daytime temperature of 35.0° and a maximum of 36.4°C. Therefore, the best approximation of the thermal lethal limit of *Thalassia* in southwest Puerto Rico is 36.5°C.

IV. DISCUSSION

A. *Biscayne Bay, Florida*

Thalassia testudinum populations in Biscayne Bay dies at +5°C above ambient; at +1°C, the standing crop and growth became difficult to distinquish from control area. Intermediate temperature regimes had marked effects on the *Thalassia* population. When release of heated effluents was diminished, some recovery of standing crop was evident. Summer heated effluents were the controlling factor in affecting the *Thalassia* beds.

Thalassia testudinum appears to be strongly seasonal in this estuary at the edge of the tropics. Growth and productivity of blades are profoundly effected by seasonal variations of climate. Abundance of blades showed seasonal distribution with a late spring peak and a mid-winter ebb in evidence. Productivity measured in grams (dry weight) produced per m^2 per day showed a strong seasonal pattern with a May maxima and a November minima. It is noteworthy that another major plant in the area had a November peak and spring low point, *i.e. Laurencia poitei* (Thorhaug and Roessler, 1977), while four species of macrogreen algae had mid-summer peaks (Thorhaug and Roessler, 1977).

The turtle grass beds at Turkey Point were of higher standing crops (2000 to 5000 blades m^{-2}) than at the effluent mouth in Card Sound (500 blades m^{-2}).

B. Guayanilla Bay, Puerto Rico

Thalassia beds in Guayanilla Bay had low biomass compared with those in other areas of Puerto Rico (Burkholder *et al.*, 1959). A preliminary study showed that the beds most exposed to the thermal effluent had significantly ($P < .05$) less biomass than control beds located in a different part of the bay. No data was available previous to thermal discharges to compare densities. Decrease in biomass correlated with increased temperature in beds of *Thalassia* subjected to the heated effluent.

Unfortunately for the sake of comparison, factors other than temperature may have contributed to these significant differences between the warmer turtle grass beds and the control beds. The large volume of water pumped through the power station caused a continuous current of heated water to flow over the nearby *Thalassia* beds. This current was strong enough to lower the organic content of the sediment and to remove the finer particles. (Burkholder *et al.*, 1959) has shown that biomass values in turtle grass beds can be directly related to particle size of substrate. Difference in biomass apparently caused by raised temperature therefore might be a result of difference in substrate.

The water leaving the heated cove often appeared more turbid than the water in the control area. Decreased illumination due to turbidity of the plume might also account for a lower biomass in the turtle grass beds nearer to the point where heated effluent was released from the cove.

C. Comparison of two sites

Elevated temperatures from the power plants in the subtropical Biscayne Bay and tropical Guayanilla Bay both had effects on *Thalassia* standing crop when temperatures exceeded +3°C above ambient summer temperatures. Artificially-elevated temperatures +2°C and below were difficult to distinguish from natural variability of control areas in terms of standing crops and variability. This indicates that subtropical and tropical seagrass communities are close to "the brink of disaster" since temperate plant communities can withstand appreciably higher temperatures above ambient without negative effects.

The exact temperature at which the two populations underwent 100% mortality is difficult to compare since the temperatures for Biscayne Bay were reported as means for a two week period with temperatures fluctuating around the mean due to diurnal, tidal, and wind fluctuations of the plume while the Guayanilla Bay temperatures were given as maximum and minimum temperatures. However, the mean temperature (30.2°C) in summer in Guayanilla Bay was very close to that of Biscayne Bay (30.5°C). Guayanilla plants at +4.3°C above ambient were still alive after many weeks of exposure. In addition, the Guayanilla Bay populations underwent multiple stress from adjacent pollution sources.

Perhaps the transplant boxes in Guayanilla Bay provide the closest approximation to the temperature data available from Biscayne Bay. Here the lowest temperature mortality was found after seven weeks in samples at mean daytime temperatures of 35°C. This same limit of +5°C above 30.5°C was the long-term temperatures at which seagrass were denuded at Turkey Point.

The differences in techniques and methods of reporting temperatures do not allow a precise comparison of upper temperature limits between Biscayne Bay and Guayanilla Bay populations. In precise laboratory experiments with marine algae from the two places, as well as other parts of the tropics, there were no differences (Thorhaug, 1976). However, general observations that sustained temperatures of +5°C above ambient is lethal to Thalassia populations and that the mean summer temperatures of Biscayne Bay (30.5°C) and Guayanilla Bay (30.2°C) were within a few tenths of a degree argue that the upper lethal limit of these two Thalassia populations are fairly close.

The most important principle for waste heat management is that tropical and subtropical nearshore ecosystems are close to the brink of disaster (Thorhaug, 1976) and that extreme caution must be applied as to releasing heat more than 2°C above ambient on nearshore grassbeds.

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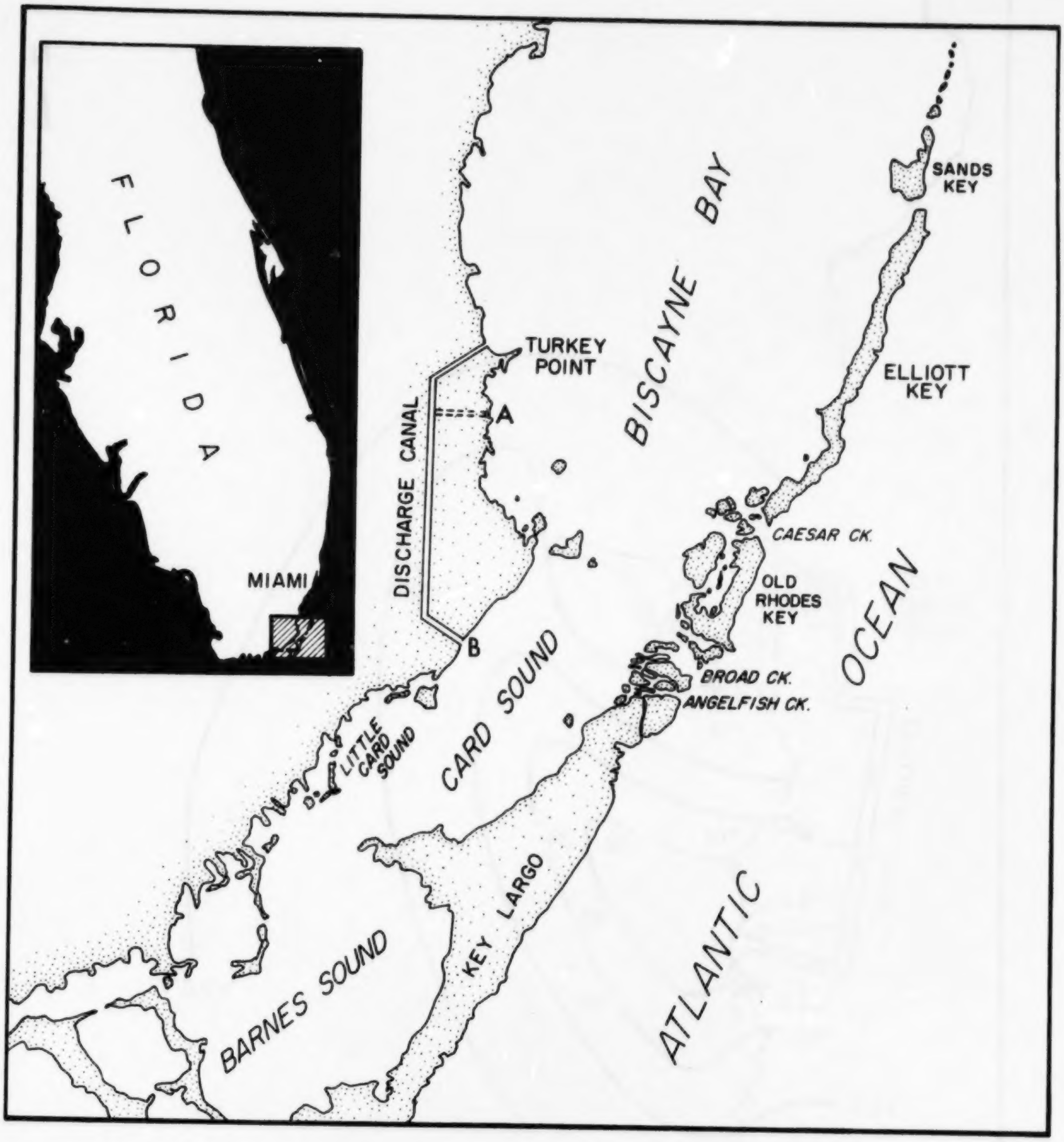
FLORIDA
MIAMI
TURKEY POINT
BISCAYNE BAY
SANDS KEY
ELLIOTT KEY
DISCHARGE CANAL
A
B
CAESAR CK.
OLD RHODES KEY
OCEAN
BROAD CK.
ANGELFISH CK.
CARD SOUND
LITTLE CARD SOUND
KEY LARGO
ATLANTIC
BARNES SOUND

Figure 1. Map of Florida showing location of study area. The letter "A" indicates the original exit point for the effluent canal, as discussed in this paper. The letter "B" indicates the new exit point in Card Sound, opened February 14, 1972.

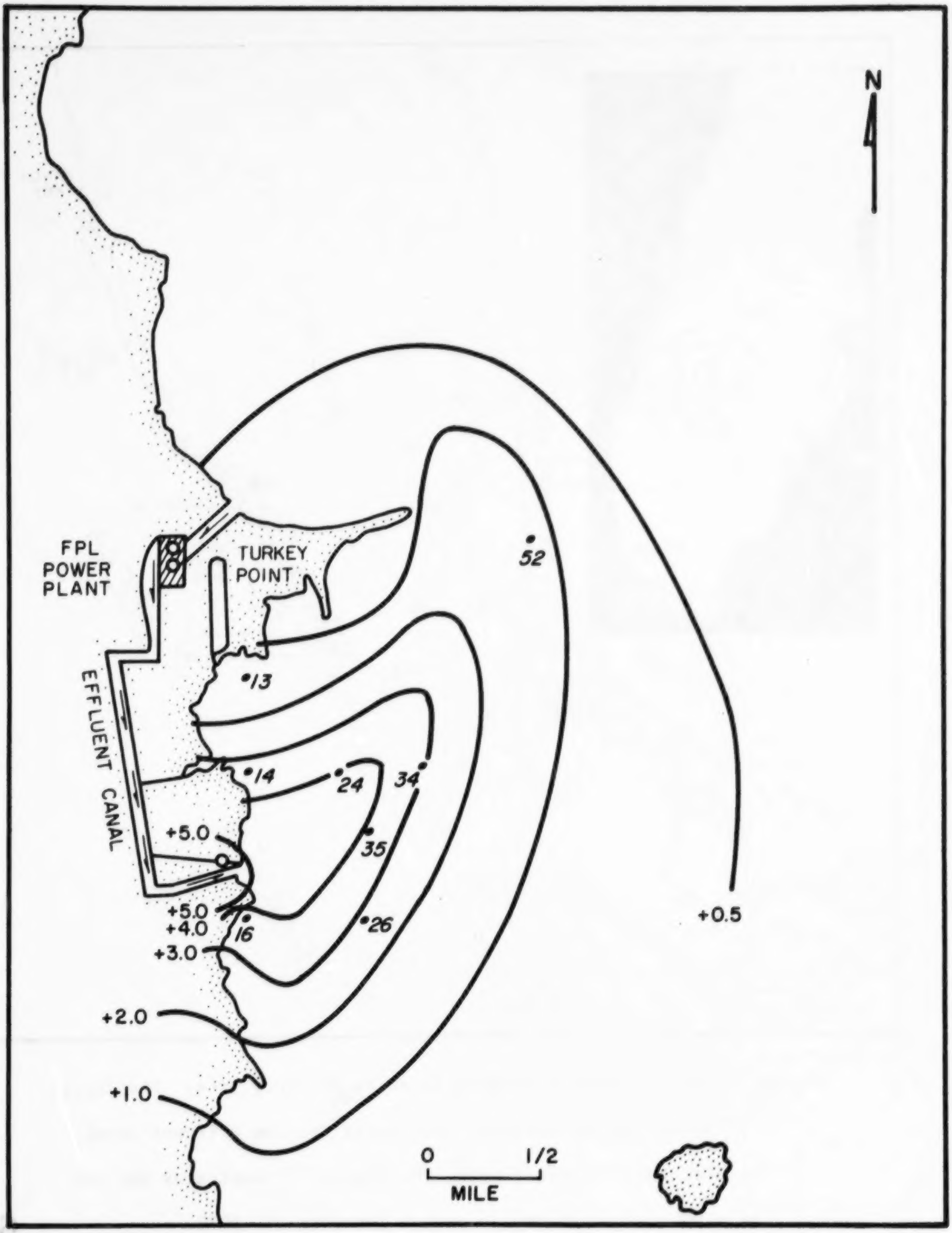
N
FPL
POWER
PLANT
TURKEY
POINT
EFFLUENT
CANAL
52
13
14
24
34
35
+5.0
+5.0
+4.0
16
26
+3.0
+2.0
+1.0
+0.5
0
1/2
MILE

Figure 2 . Mean temperature elevation above bay ambient in °C for the Turkey Point area prior to an increase in effluent flow rate on

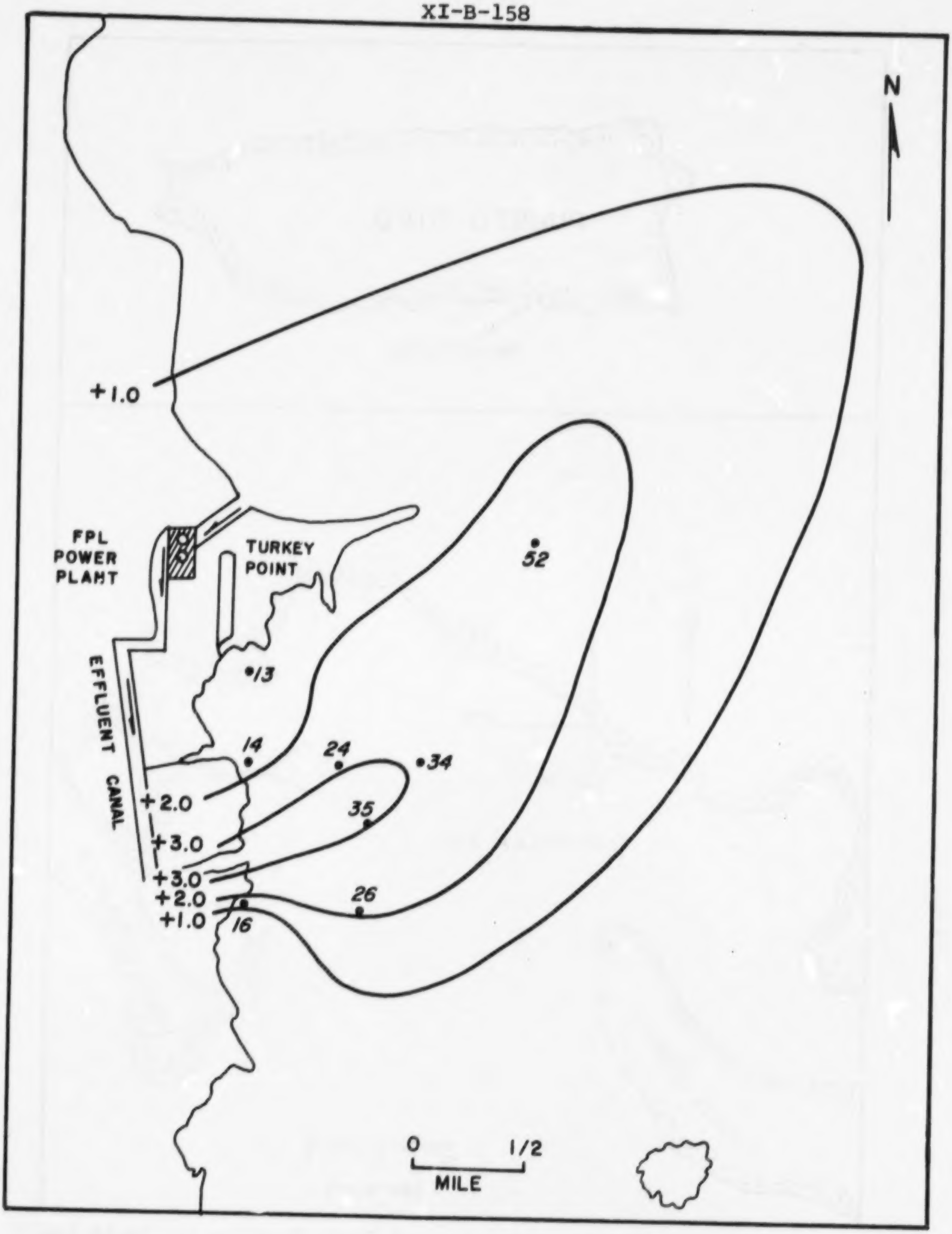
N
+1.0
FPL
POWER
PLANT
TURKEY
POINT
EFFLUENT CANAL
52
13
14
24
34
35
26
16
+2.0
+3.0
+3.0
+2.0
+1.0
0
1/2
MILE

Figure 3. Mean temperature elevation above bay ambient in °C for the Turkey Point area after July 29, 1971.

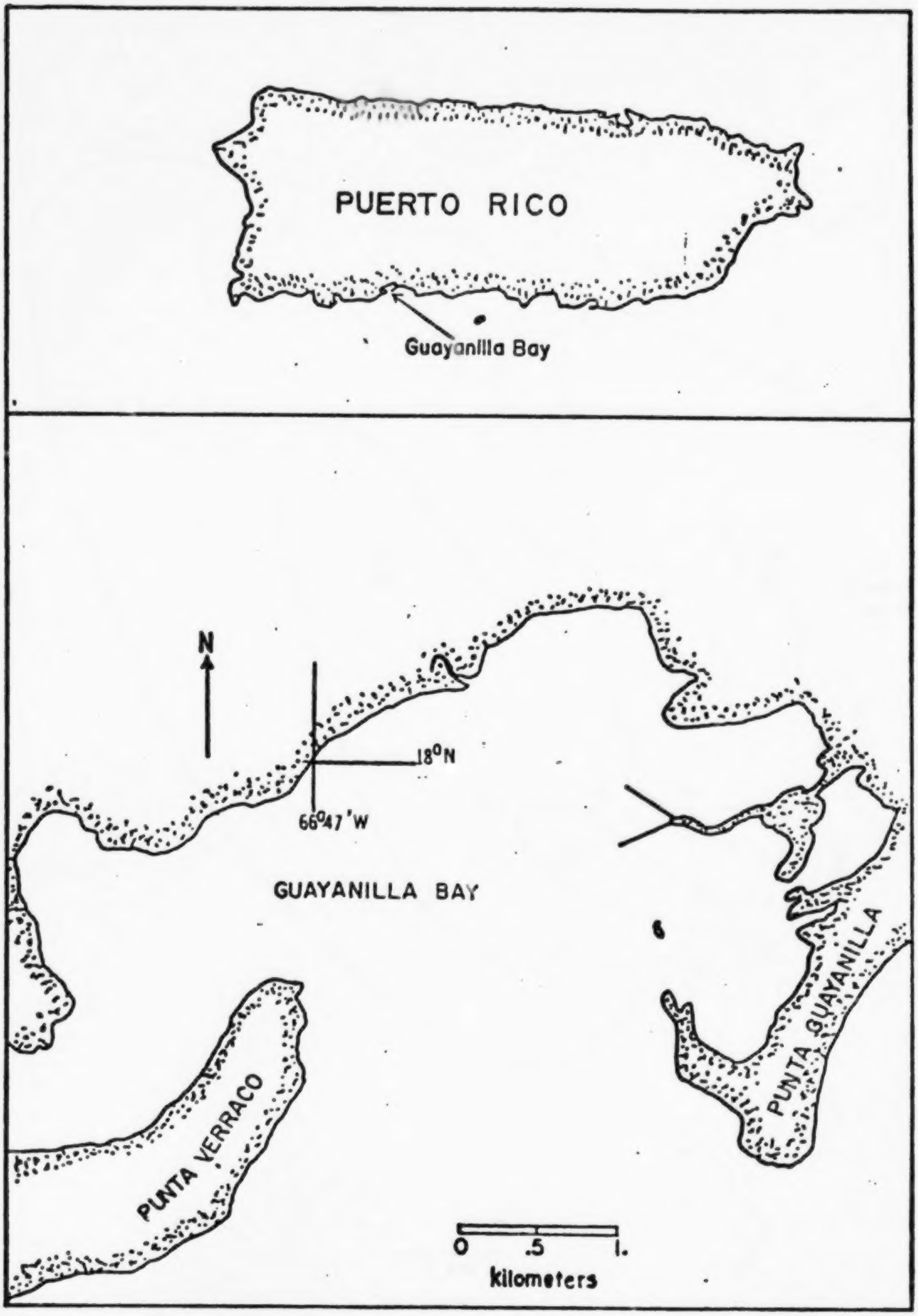
PUERTO RICO
Guayanilla Bay
N
18°N
66°47'W
GUAYANILLA BAY
PUNTA VERRACO
PUNTA GUAYANILLA
0 .5 1.
Kilometers

Figure 4. Guayanilla Bay. Location of Study Site on the South Coast of Puerto Rico.

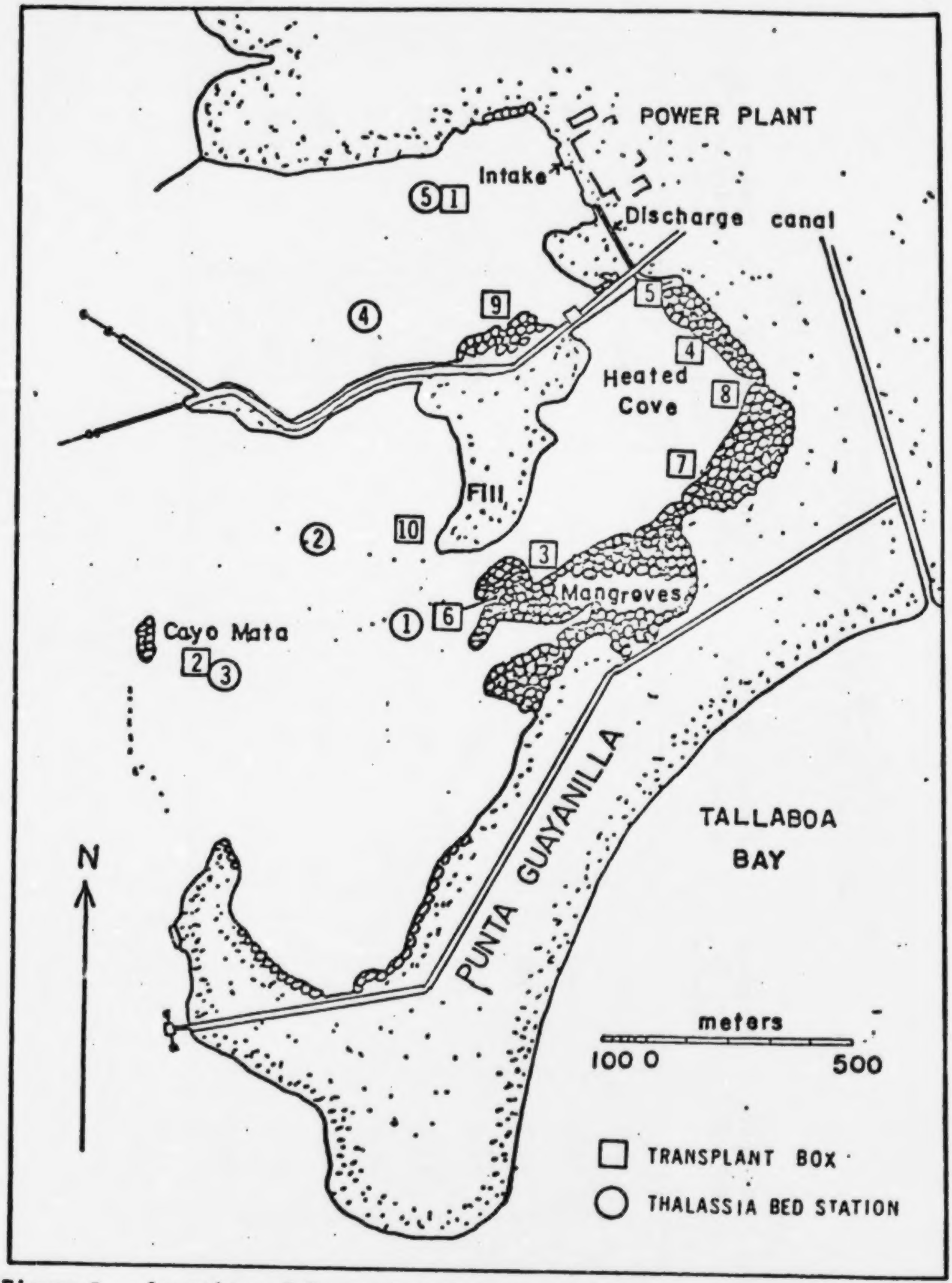
POWER PLANT
Intake
Discharge canal
Heated Cove
Fill
Mangroves
Cayo Mata
TALLABOA BAY
PUNTA GUAYANILLA
N
meters
100 0
500
TRANSPLANT BOX
THALASSIA BED STATION
1
2
3
4
5
6
7
8
9
10

Figure 5. Location of Transplant Boxes and *Thalassia* Bed Stations.

TABLE 1

Mean annual standing crop and production versus temperature above ambient for Turkey Point

	1970			1971		
Station	To above ambient	Standing crop in blades m^{-1}	Production in g dry wt $m^{-2}d^{-1}$	To above ambient	Standing crop in blades m^{-1}	Production in g dry wt $m^{-2}d^{-1}$
13	+1.5	4710	.84	+1	4897	3.01
14	+3.2	4462	.75	+1	5063	3.78
16	+3.7	3933	.68	+2	4082	3.70
24	+4.0	4325	.64	+3 to +2	5286	2.88
26	+3.0	2210	.34	+2	2080	1.70
34	+3.1	3385	.65	+1 to +2	3095	2.50
35	+3.5	2977	.48	+3	2550	1.89
52	+1.0	3660	1.14	+1 to +2	4313	5.18
Mouth	+5.0	0	0	+4	0	0

TABLE 2

Mean Annual standing crop and production
versus station in Card Sound, Florida

	Station	1971 Abundance in blades m^{-2}	1971 Production in g dry wt m^2	1972 Abundance in blades m^{-2}	1972 Production in g dry wt m^2	1973 Abundance in blades m^{-2}	1973 Production in g dry wt m^2
Control	0403	2051	1.2	1906	1.3	1967	1.2
	0503	429	0.3	453	4.3	426	4.3
	0703	496	0.3	544	0.9	645	0.9
	0504	1047	0.6	882	0.9	868	0.9
	0704	1138	0.6	881	0.5	798	0.7
Effected in 1972	0603	531	0.4	497	0.4	384	0.3
	0604	912	0.6	741	0.9	825	0.9

TABLE 3

Recorded daytime temperatures of Thalassia transplant box stations and Thalassia bed stations in Guayanilla Bay, Puerto Rico

Transplant Box Station	Description	Date Started	Minimum Temperature	Maximum Temperature
1	Control	10/14	27.2	31.2
2	Sample	10/14	28.5	34.0
3	Sample	10/14	34.5	39.0
4	Sample	10/14	35.1	39.6
5	Sample	10/14	35.4	41.0
6	Sample	10/28	30.0	34.8
7	Sample	12/10	34.2	38.5
8	Sample	12/10	34.0	39.1
9	Control	12/10	27.5	30.0
10	Sample	12/16	29.0	32.0

Thalassia Bed Station	Description	Maximum Temperature	Average Degrees Above Ambient
1	Sample	35.0	4.43
2	Sample	33.0	3.33
3	Sample	34.0	2.69
4	Control	31.1	-0.10
5	Control	31.1	0.10

TABLE 4

Biomass of *Thalassia* Plant Parts and Standing Crop in Existing Turtle Grass Beds in Guayanilla Bay, Puerto Rico

Stations	1		2		3		4		5	
Temperatures (degrees C)										
Mean	33.2		32.2		31.6		28.8		29.0	
Maximum	35.0		33.0		34.0		31.1		31.1	
Difference from control area	+4.3		+3.3		+2.7		-0.1		+0.1	
Grams Dry Weight/meter square*	$\overline{X}$	s	$\overline{X}$	s	$\overline{X}$	s	$\overline{X}$	s	$\overline{X}$	s
Green leaves	40.0	42.5	41.0	20.0	108.0	45.5	112.0	22.5	151.0	59.5
Dead leaves	129.5	121.0	127.9	64.5	277.0	94.0	303.5	35.5	293.0	78.5
Rhizomes	82.5	54.0	190.5	84.0	278.0	83.5	293.0	140.0	190.5	96.0
Vertical shoots	31.5	29.0	121.0	66.0	75.0	31.5	79.5	44.0	161.0	131.5
Roots	42.0	42.0	194.5	46.0	207.5	59.5	348.5	84.0	378.0	172.0
Sheaths	41.0	31.5	87.5	40.0	169.0	73.5	167.5	59.5	187.5	103.0
Total	366	272	761	200	1114	173	1302	232	1360	418

*$\overline{X}$ = mean weight, s = standard deviation based on 0.02 square meter samples